Minnesota Geological Survey, Open File Report 07-05, The Lake Elmo downhole logging project: hydrostratigraphic characterization of fractured bedrock at a perfluorochemical contamination site

ERRATA

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THE LAKE ELMO DOWNHOLE LOGGING PROJECT: HYDROSTRATIGRAPHIC CHARACTERIZATION OF FRACTURED BEDROCK AT A PERFLUOROCHEMICAL CONTAMINATION SITE

Anthony C. Runkel

John Mossler

Robert Tipping

Minnesota Geological Survey

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EXECUTIVE SUMMARY

This report summarizes the results of a one-year investigation by the Minnesota Geological Survey to provide the Minnesota Pollution Control Agency with information on bedrock properties and groundwater flow at a perfluorochemical contamination site in the Lake Elmo area of Washington County Minnesota. The information was largely derived from borehole geophysical logging of water wells within the study area. The principal results are as follows:

- 185 wells were successfully logged with some combination of natural gamma, caliper, or multi-parameter borehole logging tools. Nineteen wells had access issues that prevented geophysical logs from being collected. 22 wells were also flowmeter logged.
- The information collected allowed the hydrostratigraphic properties of the bedrock in the study area to be characterized, including description of matrix properties and secondary pores.
- Most wells in the study area drew water from the Shakopee aquifer and/or the lower St. Peter aquitard.
- Hydraulically significant fractures/solution cavities are common in both of these hydrogeologic units. Higher densities of these features appear to correlate to specific stratigraphic positions.
- The Shakopee aquifer and lower St. Peter aquitard are both likely strongly vertically anisotropic, with high to very high conductivity bedding plane fracture networks and coarse clastic beds separated from one another by aquitards composed of fine clastic or carbonate rock that is relatively resistant to vertical flow.
- Uncased boreholes in the study area collectively breach all aquitards in the lower St. Peter and upper Shakopee Formations and prior to abandonment may have played a significant role in the hydrogeologic system, providing pathways across intervals that otherwise would have been more resistant to vertical flow. Incompletely sealed annular spaces may similarly be important.

INTRODUCTION

The Minnesota Pollution Control Agency (MPCA) and Minnesota Department of Health are actively involved in detecting and remediating perfluorochemical contamination of groundwater in the Twin Cities Metropolitan area. A perfluorochemical plume in the Lake Elmo area (Fig. 1) of Washington County contaminated the water supply of more than 285 residents in that area. As a result, a municipal water system has been connected to more than 200 residents, and domestic wells in the area were abandoned. This report summarizes the results of a project by the Minnesota Geological Survey to collect downhole geophysical data from nearly 200 of these domestic wells before they were sealed as part of the abandonment process. Over 95 percent of these wells extract water from the lower one-half of the St. Peter Sandstone or upper part of the Shakopee Formation (Fig. 2), with the remaining wells open to overlying unconsolidated glacial deposits. The downhole geophysical data are used to determine rock properties and flow characteristics of these bedrock aquifers. The results will be used by the MPCA to help better determine the three dimensional extent of contamination, and in particular provide insight into the role of groundwater flow through fractures. Such information will assist the MPCA in determining appropriate remedial monitoring actions in a cost effective manner.

STUDY AREA AND DATA COLLECTION

Geophysical logs were collected from 185 wells (Appendix A) in an area of about one square mile, about 2 miles southwest of the city of Lake Elmo, Washington County, Minnesota (Fig. 1). A relatively small number of available wells (19 at the date of this report) were not logged because of access issues. Data were collected using one or more borehole geophysical tools that in combination allow interpretation of a number of rock and water properties (Figs. 2, 3, 4). Natural gamma logs are largely a measure of rock and sediment potassium content, which is used to distinguish relatively coarse-grained sandstone from finer grained sandstone, siltstone, and shale, and to recognize bedrock intervals dominated by carbonate rock (limestone or dolostone) (Fig. 2). Caliper logs are a measure of borehole diameter (Fig. 3). Sharp positive deflections in such logs are used to recognize secondary pores such as fractures, although fractures with relatively narrow aperture (fractions of an inch) yet potentially hydraulically significant, are not consistently demarked on these logs (see appendix explanation). Video logs collected with a downhole camera were obtained from two boreholes by the Minnesota Department of Health, and they allow direct, visual observation of fractures in uncased parts of boreholes (Fig. 3; Appendix B). Caliper, single point resistivity logs, and video logs also can indicate the depth of casing bottom.

A Multi-Parameter E-Log tool measures a variety of water properties in addition to the standard gamma and single point resistivity logs described above. Sharp deflections in fluid resistivity and temperature curves collected with the Multi-Parameter E-Log tool ("Multi-Parameter tool") are an indication of ambient water movement through secondary pores such as fractures (e.g. Fig. 4A). Depth to static water level in a borehole is marked by an abrupt positive deflection in single point resistivity curves.

Twenty-two wells were logged with an Electro-Magnetic (EM) Flowmeter tool that measures vertical flow speed (water movement up or down a borehole), in addition to fluid resistivity and temperature. This information is used to identify discrete fractures and relatively high permeability sandstones that accommodate active water flow in response to either ambient or induced hydraulic gradients (Figs. 3, 4A, Appendix C). Boreholes with measurable ambient vertical flow also indicate the presence of aquitard(s) between the intervals through which water enters or exits the open part of a borehole. Flowmeter logs were also collected from four boreholes under stressed conditions of water injection at rates between 5 and 10 gallons per minute (e.g. Figs. 3, 4B; Appendix C). Injection logging provides information necessary to quantify the hydraulic conductivity of individual sandstone intervals and fractures. Flowmeter logging procedures are described in greater detail in Runkel and others (2003, 2006).

GEOLOGIC SETTING

Unconsolidated glacial deposits dominated by sandy till and sand bodies range in thickness from less than 10 feet in the western part of the study area to as much as about 100 feet in the extreme northeastern part of the study area (Fig. 5; Meyer and others, 1990). Bedrock beneath the glacial deposits is gently tilted a few degrees to the west (Fig. 5; Mossler and Bloomgren, 1990). The upper 250 feet of bedrock, in ascending stratigraphic order, consists of the Shakopee, St. Peter, Glenwood and Platteville Formations. The bedrock is progressively more deeply eroded eastward across the study area, and therefore uppermost bedrock beneath the glacial deposits includes the Platteville and Glenwood Formations in the west, St. Peter Sandstone in the central study area, and Shakopee Formation to the east (Fig. 5).

BEDROCK HYDROSTRATIGRAPHIC PROPERTIES

Matrix

The bedrock in the Lake Elmo study area is composed of the three fundamental rock matrix components (Figs. 2, 5) described in Runkel and others (2003). A coarse clastic component consists of fine- to coarse-grained sandstone with 15 to 30 percent porosity and a relatively high horizontal hydraulic conductivity of 10 to 20 ft/day. The fine clastic component is very fine grained sandstone, siltstone and shale with a porosity of five to 30 percent and a relatively low horizontal conductivity of 10^{-10} to 10^{-5} ft/day. Carbonate rock has both a low porosity and conductivity, generally less than 10 percent and 10^{-7} to 10^{-3} ft day, respectively. All three rock components are anisotropic, with horizontal conductivity typically one to two orders of magnitude greater than vertical.

The Shakopee Formation is dominated by low conductivity carbonate rock (dolostone), with subordinate beds of coarse clastic sandstone that are a few inches to as much as about three feet thick (Figs. 2, 5) (Runkel and others, 2003). These interbeds have a relatively high matrix porosity and permeability. Thin to very thin beds of shale are present in some coarse clastic intervals.

The St. Peter Sandstone can be divided into two parts based on matrix properties (Figs. 2, 5). The upper 85 feet is composed of the coarse clastic component, chiefly friable, fine- to medium-grained sandstone. Laboratory tests of rock samples and specific capacity data indicate that the upper St. Peter Sandstone has a matrix conductivity that typically ranges between 10 and 20 ft/day (Runkel and others, 2003). The lower 75 feet of the St. Peter Sandstone also contains the coarse clastic component, but differs from the upper part in having interbeds of fine clastic strata. Six beds composed largely of the fine clastic component, ranging in thickness from about 5 to 15 feet, were traced across the study area using natural gamma logs (Figs 2, 5). Examination of core collected about 2.5 miles from the study area (core PC-45, unique number 737655) indicates that these beds are composed mostly of very fine-grained sandstone and siltstone. The lowermost part of bed one also contains layers of shale as much as a few inches thick.

Matrix hydraulic conductivity in the lower 75 feet of the St. Peter Sandstone will be greatly variable and strongly anisotropic. The hydraulic conductivity of the coarse clastic component was measured in the study area at 15.6 ft/day (Fig 4B, Table 1), within the range of values for sandstone of similar grain size in the St. Peter Sandstone measured elsewhere in southeastern

Minnesota (Runkel and others, 2003). The very fine grained sandstone and siltstone interbeds are poorly cemented, and therefore likely have a conductivity within the upper range of values for the fine clastic component described in Runkel and others (2003), about 10^{-5} ft/day. Bulk vertical conductivity of lower St. Peter has been estimated to be about 10^{-3} ft/day (Schoenberg 1990).

The Glenwood Formation is composed chiefly of the fine clastic component, mostly shale and siltstone. Laboratory tests of rock samples from elsewhere in southeastern Minnesota indicate that it has a vertical conductivity of about 10^{-8} ft./day (Runkel and others, 2003). Thin to very thin coarse clastic interbeds with a relatively high porosity and conductivity are locally a minor component of the Glenwood Formation. The overlying Platteville Formation is composed chiefly of low conductivity material, dominated by carbonate rock with thin to very thin shale laminae.

Secondary pores

A schematic depiction of bedrock secondary pores in the study area is shown in Figure 5. It incorporates information collected within the study area and also draws upon information gathered regionally (Runkel and others, 2003). The data we collected from the study area are consistent with regional characterizations that depict the uppermost 50 to 200 ft of bedrock as ubiquitously fractured, and with fracture density and aperture size decreasing with depth. Systematic fractures ("joints") are flat-sided openings oriented perpendicular to bedding, have apertures up to several inches, and a spacing of several meters. They are known in outcrop to extend vertically from a few inches to as much as several tens of feet, terminating at beds that have material properties relatively resistant to through-going fractures. For example, systematic fractures in exposures of the Platteville formation commonly terminate in the underlying Glenwood Formation. Nonsystematic fractures are irregular, curved to straight fractures that commonly intersect bedding at a lower angle than systematic fractures, and generally have narrower apertures. They are more densely distributed than systematic fractures and commonly extend vertically no more than a few feet. Bedding plane fractures are openings that preferentially align parallel to bedding, with apertures as wide as about three inches (e.g. Fig. 6). Such bedding plane fractures are known to be interconnected at scales much greater than that of the study area (Runkel and others, 2006). Solution cavities, commonly referred to as "vugs", that do not appear to correspond to any of the mechanical fractures described above are a fourth type of secondary pore. Solution can also enlarge the apertures of mechanical fractures. Formations dominated by carbonate rock, such as the

Shakopee and Platteville Formations, commonly have relatively large secondary pores compared to clastic rock at least in part because of the presence of large solution cavities and solution enlargement of mechanical fractures.

Uncased boreholes are a secondary pore created through construction of water wells. Prior to well abandonment there were nearly 200 water wells in the study area with open-hole intervals that most commonly ranged from four to six inches in diameter, and in length from a few feet to as long as about 75 feet (Fig. 5). Ungrouted or otherwise incompletely sealed annular space between well casings and boreholes similarly can be considered a type of secondary pore that is vertically extensive and has a relatively large aperture. Although we cannot directly measure the apertures of natural vertical fractures in the study area, open-hole intervals and ungrouted annular spaces may be among the largest secondary pores in terms of aperture size and vertical extent in the study area.

Borehole logs in the Lake Elmo study area were particularly useful for documenting the presence of bedding plane fractures and nonsystematic fractures in the lowermost 80 feet of the St. Peter Sandstone and upper 50 feet of the Shakopee Formation. Caliper and video logs indicate that both intervals are characterized by relatively abundant bedding plane fractures (e.g. Fig. 3; Fig. 6). They appear to be most abundant in fine clastic beds or at the contacts between fine clastic and coarse clastic layers in the St. Peter Sandstone (Fig. 7A). The greatest density of bedding plane fractures is within, or at the boundaries of, fine clastic beds two, three and four.

Ambient flow through bedding plane fractures was documented across a wide range of stratigraphic positions in the lower one-half of the St. Peter Sandstone and upper 50 feet of the Shakopee Formation. It was especially common at three discrete positions in the Shakopee Formation and in fine clastic beds one through three in the lower St. Peter Sandstone (Figs. 7B, C). Hydraulic conductivity of 10 individual bedding plane fractures was measured in three wells and ranged from 110 to 40,400 ft/day (Table 1, Appendix C). These values are consistent with measurements of bedding plane fractures in other Paleozoic formations across southeastern Minnesota. For example, studies by Runkel and others (2003; 2006) and Tipping and others (2006) demonstrate that such fractures vary greatly in conductivity and that individual fractures with apertures of only a few inches can have orders of magnitude greater conductivity than even the relatively highly permeability coarse clastic rock matrix. Thus the Lake Elmo tests should be considered a small sample of what is likely widely variable conductivity for individual fracture networks.

BEDROCK HYDROGEOLOGIC SYNTHESIS

Information collected from wells in the Lake Elmo study area in combination with our knowledge of hydrogeologic characteristics of Paleozoic bedrock regionally across southeastern Minnesota provide insight that will lead to a better understanding of the distribution of perfluorochemical contaminants, and for formulating a remediation plan. The results of our borehole geophysical logging indicate that the Shakopee Formation in the study area has attributes typical of the formation across all of southeastern Minnesota (Runkel and others 2003; Tipping and others, 2006). It is a karstic aquifer in which the largest volume of groundwater is transported along secondary pores, with bedding plane fracture networks accommodating the bulk of horizontal flow. Hydraulic conductivity of bedding plane fractures in the Shakopee Formation in southeastern Minnesota varies greatly, is known to commonly exceed several thousand ft/day, and flow speeds have been measured at hundreds of ft/day or faster. Intervals with bedding plane fractures are commonly separated vertically from one another by carbonate rock with relatively few interconnected fractures. Ambient flow within boreholes open only to the Shakopee Formation (Fig. 8, Appendix C) in the study area and elsewhere across southeastern Minnesota indicates that these latter intervals serve as local aquitards that hydraulically separate bedding plane fracture networks.

The St. Peter Sandstone can be divided into an upper aquifer and a lower aquitard (Fig. 2). The uppermost 85 feet of the St. Peter is a fine- to medium-grained sandstone aquifer that has a relatively high matrix porosity and permeability, and in addition contains fractures that can be expected to have much greater permeability. The lower 75 feet of the St. Peter Sandstone is an aquitard that is markedly anisotropic in a vertical direction. The fine clastic interbeds have a bulk vertical conductivity estimated at 10^{-3} ft/day (Schoenberg, 1990), sufficient to sustain artesian conditions across a large part of the Twin Cities Metropolitan area (Hall and others, 1911) and to maintain hydraulic heads above and below that differ by as much as a few tens of feet (Kanivetsky and Cleland, 1992). The presence of ambient vertical flow in wells open to the lower St. Peter (Fig. 8, Appendix C) similarly suggests that individual fine clastic intervals are of sufficiently low vertical conductivity to serve as aquitards. In contrast, in a horizontal direction the lower St. Peter Sandstone has properties comparable to Paleozoic sandstone aquifers in southeastern Minnesota. Coarse clastic interbeds have moderate to high intergranular hydraulic conductivity, and bedding plane fractures with a significantly higher conductivity are common throughout the lower St. Peter, including within the fine clastic intervals that serve as aquitards in a vertical direction.

Highly anisotropic bodies of rock such as the Shakopee aquifer and lower St. Peter aquitard are commonly hydrogeologically compartmentalized because individual bedding plane fractures and coarse clastic beds are hydraulically separated from one another by fine clastic or carbonate rock that is resistant to the development of throughgoing vertical fractures (e.g. Eaton and Bradbury, 2003). As a result, the chemical attributes of the groundwater potentially can be similarly compartmentalized. We therefore have divided the lower St. Peter Sandstone strata into subunits (Fig. 2) that can be compared against water chemistry data in an effort to better understand the distribution of contaminants across the study area. These subunits are not proven to be distinct hydrogeologic units, instead they simply represent the finest resolution at which we confidently could subdivide these strata consistently across the study area using our borehole logging data.

Flowmeter logs and static water level measurements provide insight into hydraulic head distribution within the lower St. Peter aquitard and the upper part of the Shakopee Aquifer. Ambient flow directions in 13 of the 22 wells logged with the EM flowmeter indicate that the highest head across most or all of the study area is in units A and B of the St. Peter Sandstone and unit B of the Shakopee aquifer (Fig. 8). This relatively high head in the lowermost St. Peter Sandstone and uppermost Shakopee Formation drives upward ambient flow in most boreholes open only to the St. Peter Aquitard, and downward flow in most wells open to the Shakopee Aquifer. This, and any other variability in head, appears to be relatively small across the study area. Static water level variability across the study area was insufficient to allow us to discern consistent vertical differences in head, indicating that any such head differentials are likely to be less than 5 feet. The rates of ambient flow we measured are relatively low (e.g. Fig. 3, 4A, Appendix C) compared to flowmeter logging conducted elsewhere in southeastern Minnesota, which is also indicative of relatively small head differences in rocks that have a high conductivity capable of permitting much higher flow rates.

The Glenwood and Platteville Formations are known to have marked variability in hydrogeologic properties in geologic settings similar to those in the study area. Both formations are composed largely of low conductivity matrix, and are known to serve at least locally as aquitards with a low bulk vertical conductivity (Runkel and others, 2003). However, both units are also known to contain vertical fractures that locally serve as conduits that provide hydraulic connection to the underlying St. Peter Sandstone. The Platteville Formation is especially hydrogeologically complex in settings where it subcrops such as in the study area. It is a karstic unit with high conductivity bedding plane-parallel secondary pore conduits and vertical fractures that can accommodate large volumes of water. Bedding plane conduits can be locally hydraulically separated from one another by intervals of unfractured carbonate rock, shale or bentonite beds that serve as aquitards.

Any characterization of hydrogeologic conditions and distribution of contamination must include assessment of the potential importance of well construction in the study area. Hart and others (2006) demonstrated that uncased parts of boreholes can significantly enhance vertical conductivity of aquitards, potentially exceeding the vertical conductivity of natural vertical fractures. Modeling studies have shown that entire contaminant plumes can be transported across aquitards from one aquifer to another via open boreholes (Lacombe and others, 1995). Prior to well sealing, the study area contained over 200 wells, most with open-hole intervals that breach one or more aquitards in the lower St. Peter Sandstone and upper part of the Shakopee Formation (Figure 5). Unsealed annular spaces may similarly provide hydraulic connection across higher stratigraphic horizons. Prior to sealing, such features provided connection between bedding plane fractures and coarse clastic intervals that would have otherwise been more effectively hydraulically separated. They may in part also account for the apparently small head differences across the St. Peter Sandstone and Shakopee Formation compared to other parts of the Twin Cities Metropolitan area.

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Well unique number	Unit	Tested feature	Horizontal hydraulic conductivity in ft/day
609537	Lower St. Peter Sandstone	Bedding plane fracture K1	10,900
609537	Lower St. Peter Sandstone	Bedding plane fracture K2	2550
609537	Lower St. Peter Sandstone	Bedding plane fracture K3	710
519084	Lower St. Peter Sandstone	Coarse clastic sandstone interval K1	16
613401	Upper Shakopee Formation	Bedding plane fracture K1	980
613401	Upper Shakopee Formation	Bedding plane fracture K2	340
613401	Upper Shakopee Formation	Bedding plane fracture K3	410
613401	Upper Shakopee Formation	Bedding plane fracture K4	110
569744	Lower St. Peter Sandstone	Bedding plane fracture K1	42,400
569744	Lower St. Peter Sandstone	Bedding plane fracture K2	7520
569744	Lower St. Peter Sandstone	Bedding plane fracture K3	18,500

Table 1. Horizontal hydraulic conductivity measurements in Lake Elmo Study area. Values calculated by flowmeter logging during well injection at rates between 5 and 10 gallons per minute, according to the procedure described in Runkel and others (2006). Graphic depictions of the flowlogging conducted on these wells is in Appendix C. Values in this table are rounded from the values in Appendix C.

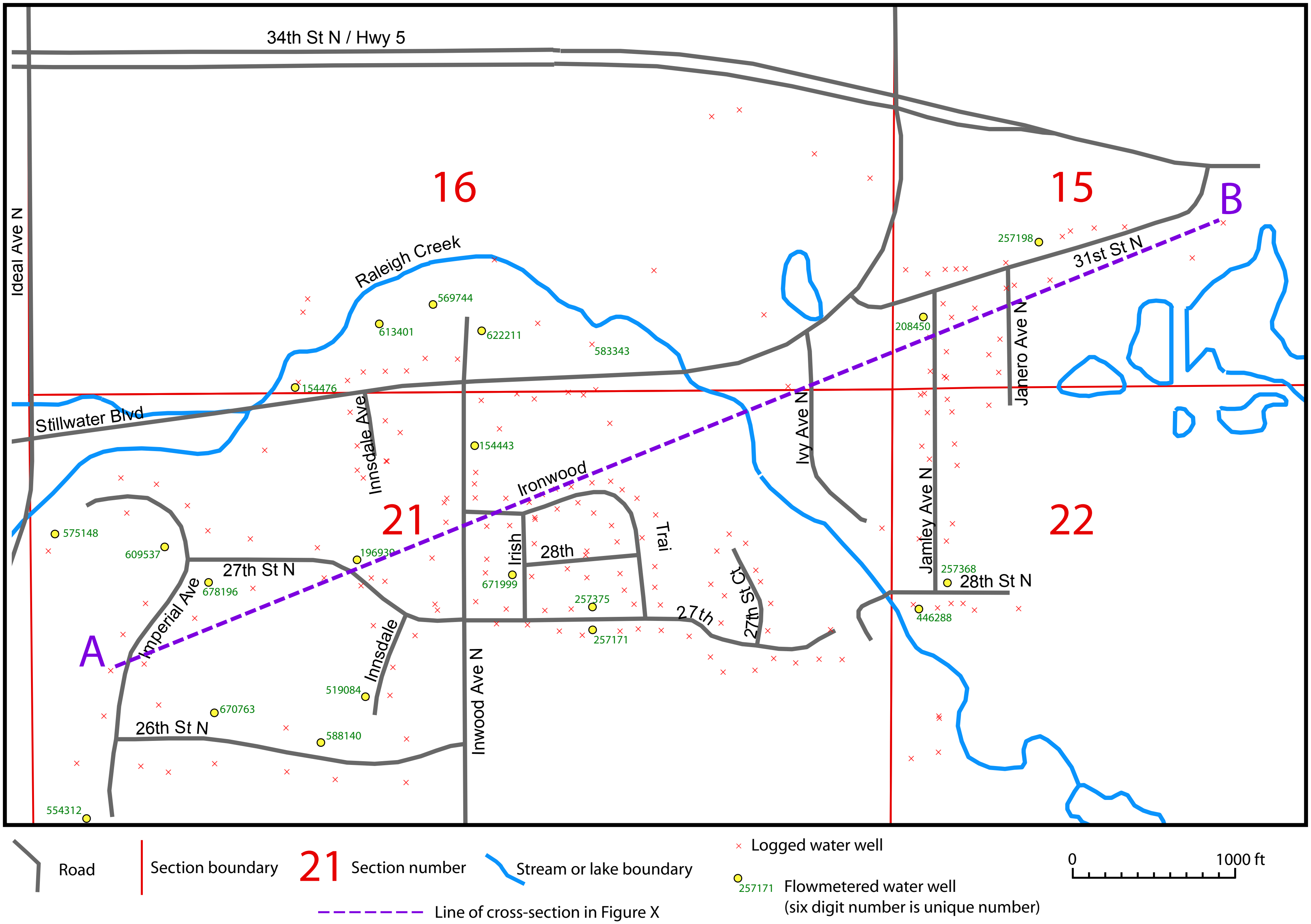


Figure 1. Lake Elmo study area showing wells for which borehole geophysical logs were collected. Dashed purple line represents line of section for cross-section in Figure 5.

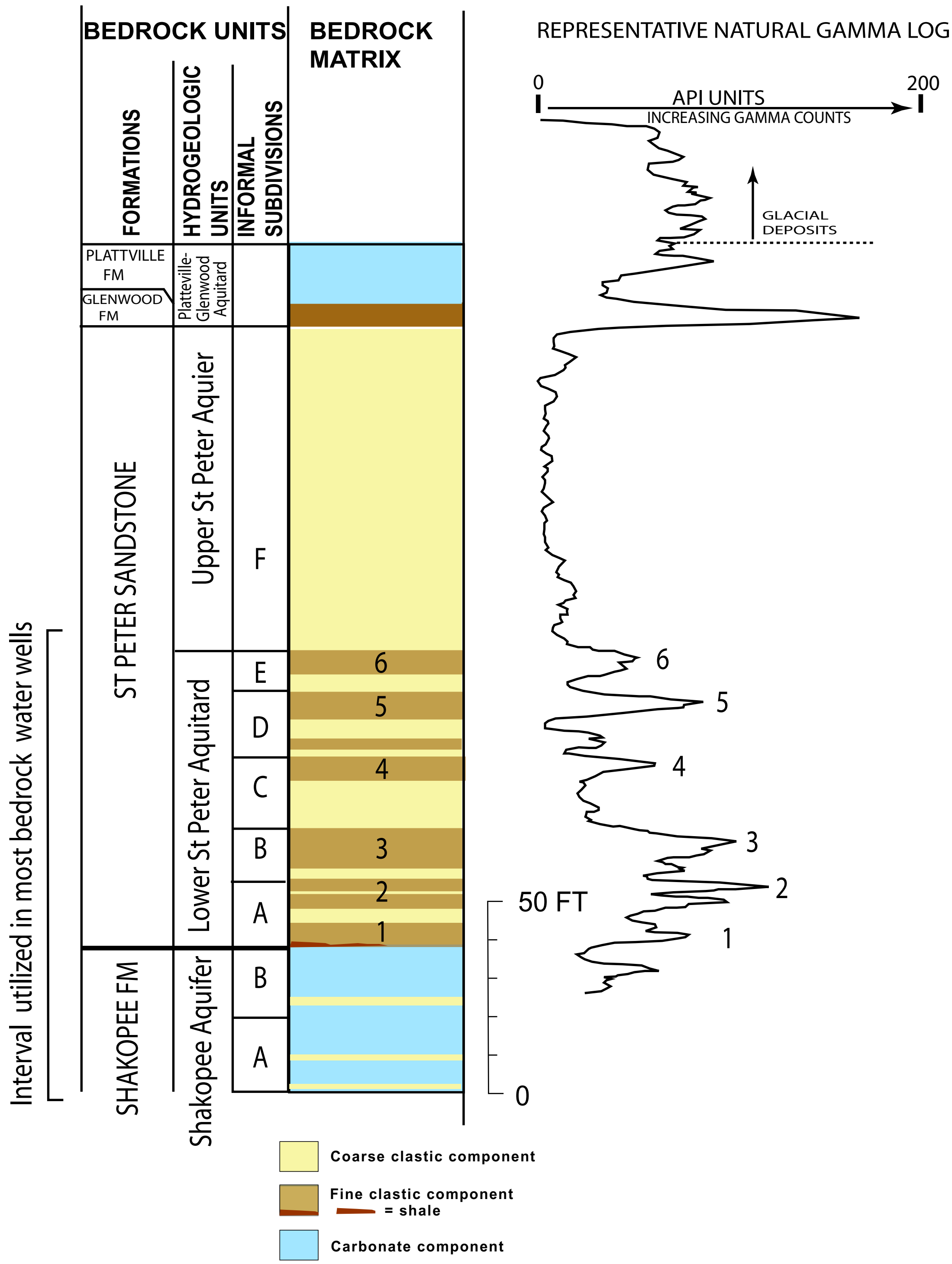


Figure 2. Stratigraphic column depicting the uppermost 250 feet of bedrock present in the Lake Elmo study area. Representative natural gamma log (unique water well number 607488) shows typical log signature used to determine rock properties. Fine clastic material is feldspathic and has a relatively high gamma log signature, coarse-clastic rock has a very low signature, and carbonate rock is moderate to very low. Numbers one through six on column and adjacent to gamma log correspond to fine clastic beds that can be traced across the study area using natural gamma logs. Informal subdivisions are explained in text.

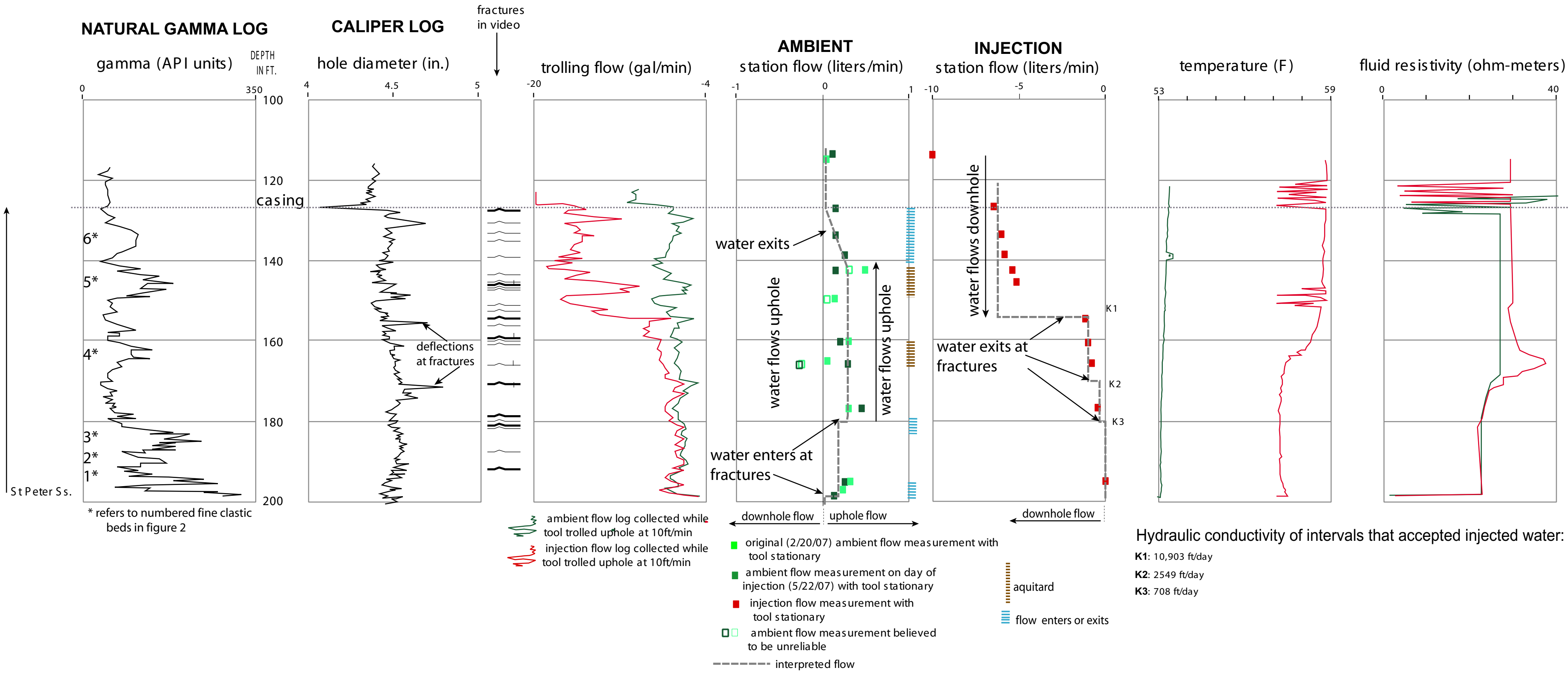


Figure 3. Example of borehole geophysical logs collected in the Lake Elmo study area. Gamma, caliper and video logs provide information on rock matrix and secondary pores such as fractures. Flowmeter logging provides information on water flow within the open borehole. In this example, injection flowmeter log shows that bedding plane fractures dominate borehole hydraulics. Water injected at rate of 22.9 liters per minute exits borehole at three bedding plane fractures (K1, K2, K3). Hydraulic conductivity of these fractures ranged from 708 to nearly 11,000 ft/day. Trolling flowmeter logs collected while trolling uphole at 10 ft/minute.For additional explanation of flowlogging procedures see text and Runkel and others (2003, 2006). Water well at 2760 Imperial Avenue North, unique number 609537. Location shown in Figure 1.

2626 Innsdale Ave N (519084)

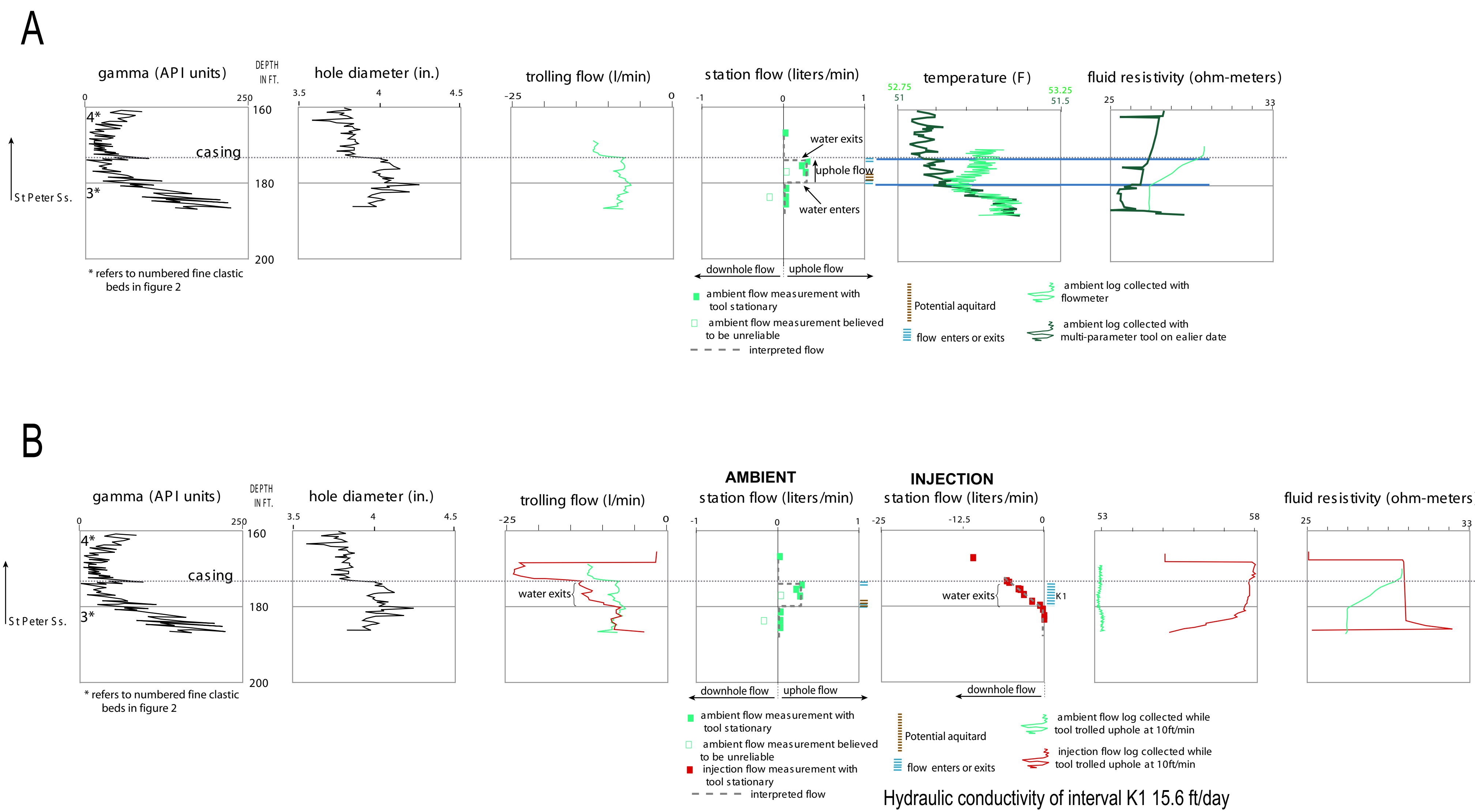


Figure 4. Example of borehole geophysical logs collected in the Lake Elmo study area. In **A)** flowmeter and multi-parameter tool logs indicate that under ambient conditions water enters borehole at about 180 ft, flows uphole at a rate of about 0.3 liters per minute, and exits about one foot or less beneath casing bottom (~174 ft). Entry and exit occurred along discrete fractures. Note shifts in fluid temperature and resistivity where water enters and exits borehole (marked by blue horizontal lines) **B)** includes data collected in the same borehole during injection of water at a rate of 22.7 liters per minute. Injected water exits the borehole gradually between 173 and 180 ft, labelled K1, indicating intergranular flow. The hydraulic conductivity of this interval is 15.6 ft/day. Trolling flowmeter logs collected while trolling uphole at 10 ft/minute. For additional explanation of flowlogging procedures see text and Runkel and others (2003, 2006). Water well at 2626 Innsdale Avenue North, unique number 519084. Location of well shown in Figure 1.

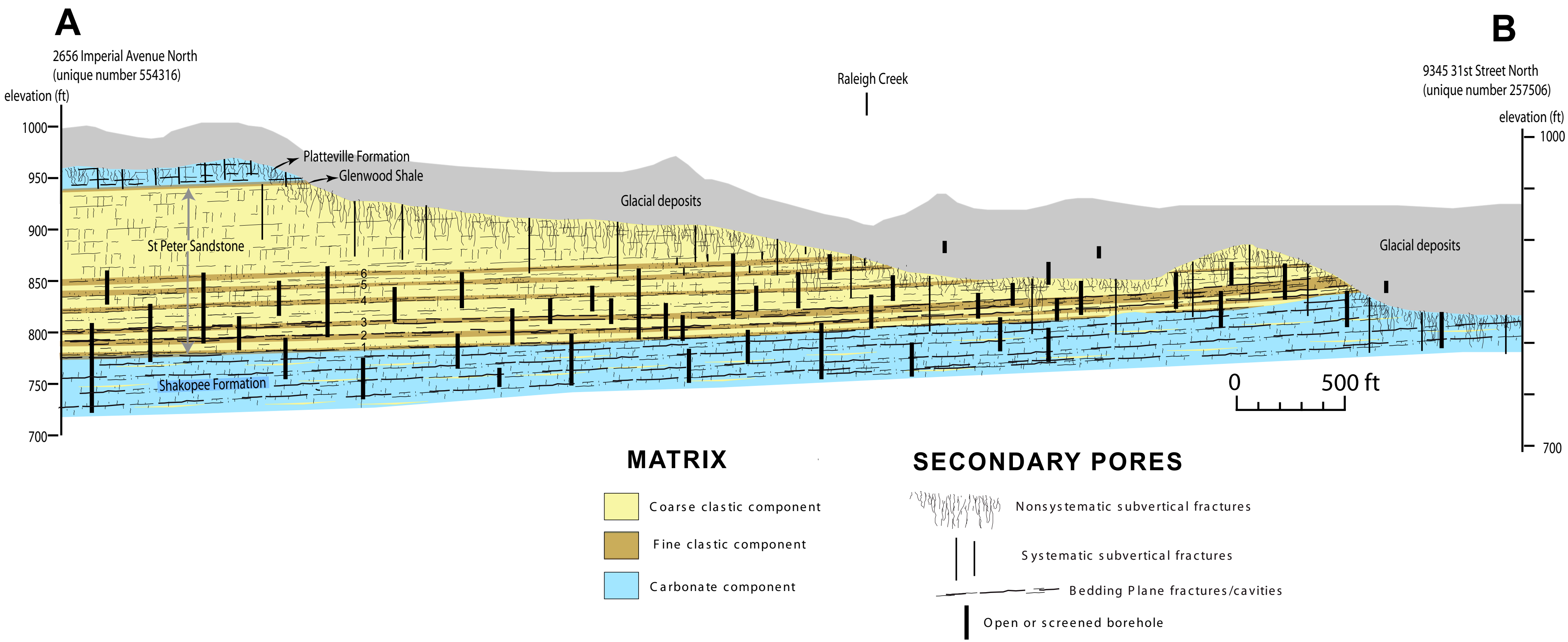


Figure 5. Geologic cross-section highlighting bedrock matrix and secondary pores in the Lake Elmo study area. Note that secondary pores are common in all bedrock formations. Geophysical logging suggests that bedding plane fractures are key features that accomodate lateral flow. Vertical fractures and open boreholes can provide hydraulic connection across aquitards that otherwise would more effectively hydraulically separate individual layers of coarse clastic sandstone and bedding plane fractures. The depiction of open or screened boreholes is schematic, intended to illustrate the manner in which water wells were commonly constructed in the study area prior to well sealing. Some features such as systematic fractures were not observed as part of this project, but are inferred to be present based on regional knowledge of similar geologic settings in southeastern Minnesota (e.g. Runkel and others, 2003). Numbers one through six in lower one-half of St. Peter Sandstone refer to the fine clastic beds numbered in Figure 2. See text for additional explanation and discussion. Line of section is shown in Figure 1.

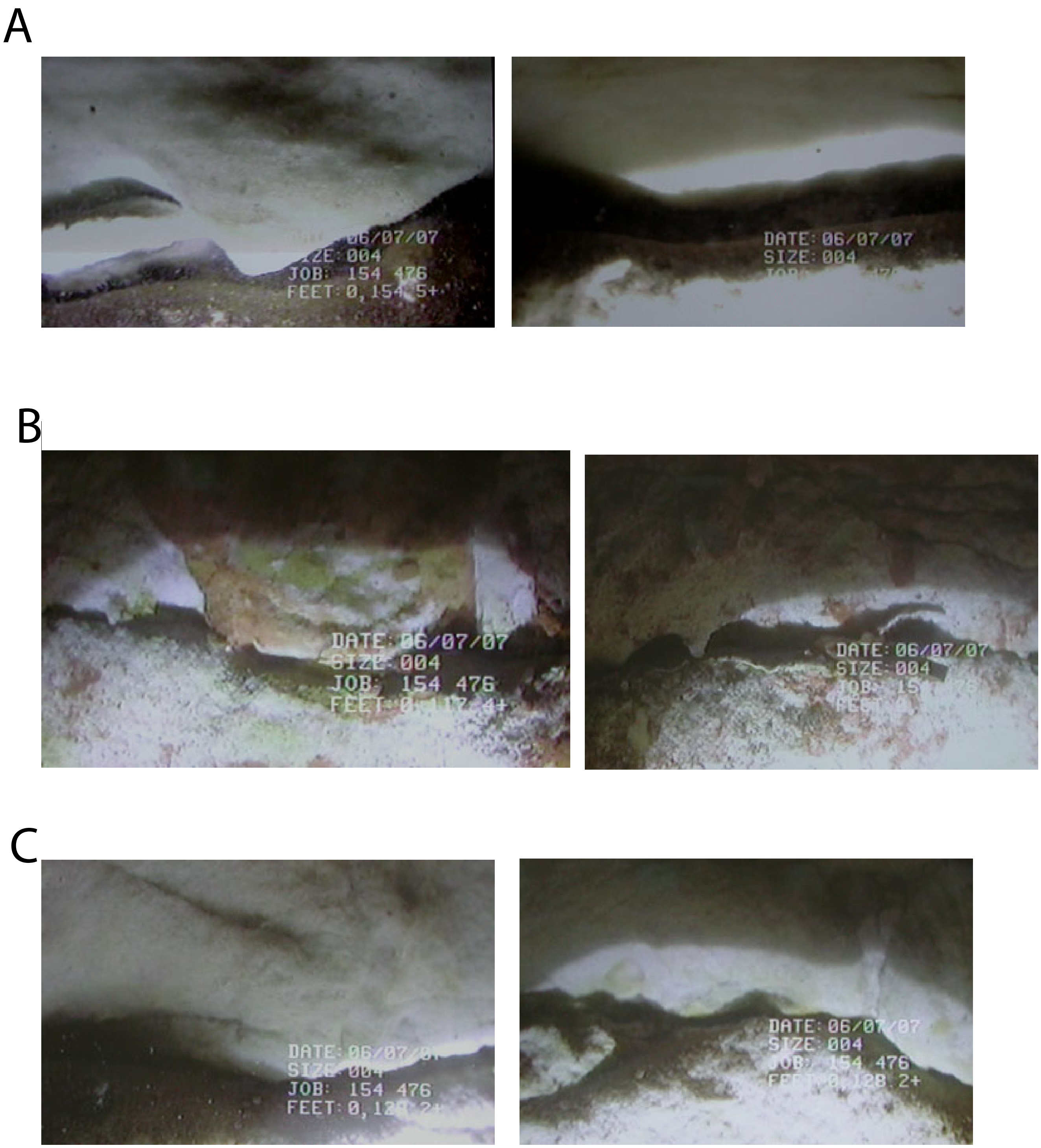


Figure 6. Bedding plane fractures in the St Peter Sandstone. Aperture width of the fractures is about one to two inches. There are two views of three fractures: **A)** Fracture at 154.5 feet in well at 2760 Imperial Avenue North (Unique number 609537), **B)** Fracture at 117.4 feet in well at 8282 Stillwater Blvd (Unique number 154476), **C)** Fracture at 128.2 feet in same well as in **B)**. The fracture in **A)** has a hydraulic conductivity of over 10,000 ft/day (see Fig. 3) Photographs derived from borehole video logs collected by Pat Sarafolean from the Minnesota Department of Health.

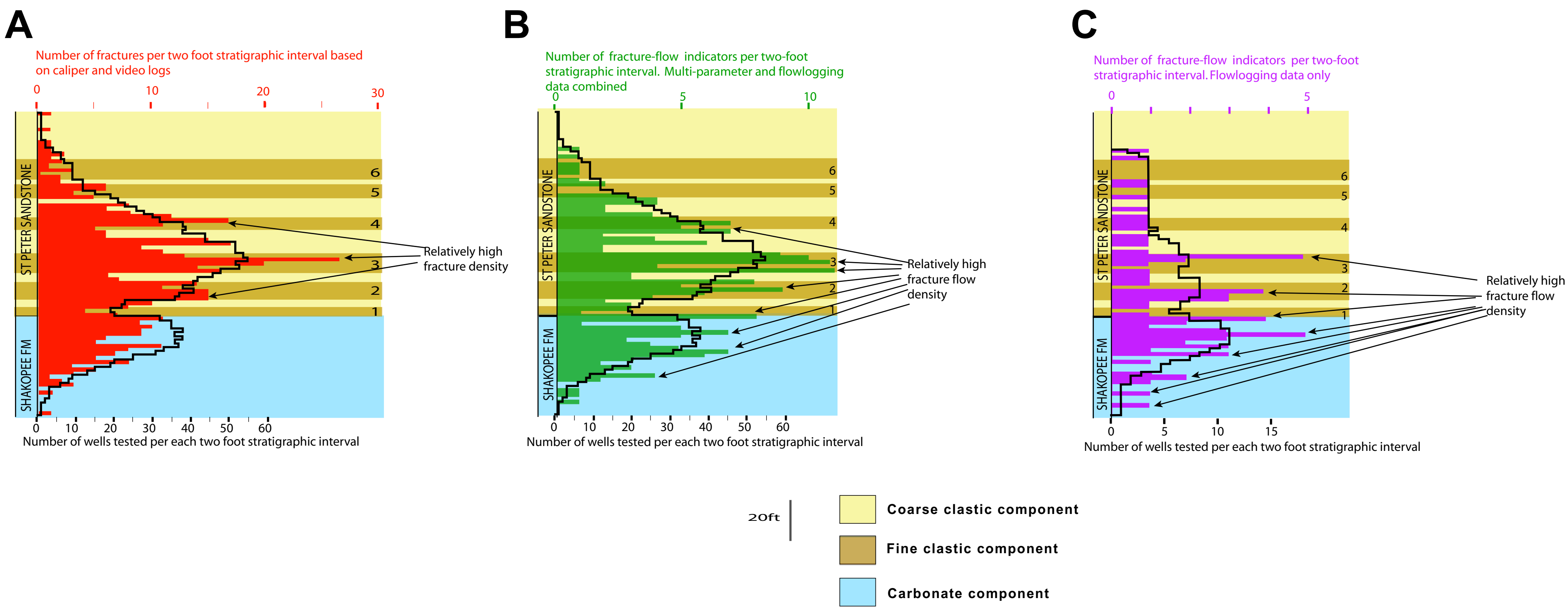


Figure 7. Graphic depiction of the relative abundance of fractures and flow through fractures at various stratigraphic positions in the St. Peter Sandstone and Shakopee Formation. Fracture and fracture flow data are compared against number of wells tested for any given stratigraphic interval to alleviate sample bias. **A)** shows relative abundance of fractures noted in caliper and video logs. **B)** shows relative abundance of fracture flow indicators based on multi-parameter and flowlogging, **C)** shows relative abundance of fracture flow indicators based on flowlogging only.

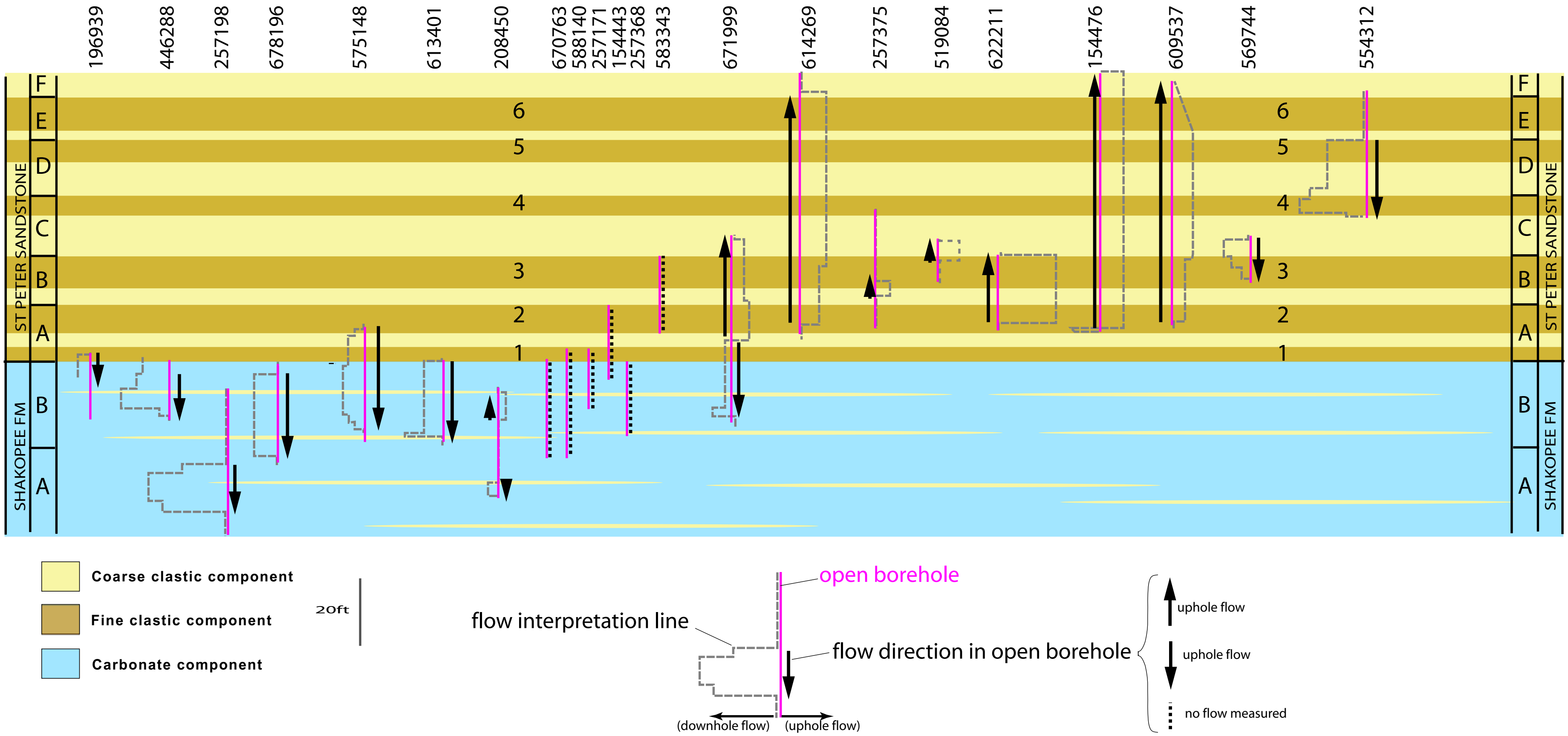


Figure 8. Ambient flow directions in open boreholes. The presence of ambient flow in most tested boreholes indicates that fine clastic beds in the lower St Peter Sandstone and carbonate rock intervals in the Shakopee Formation are aquitards. Ambient flow directions indicate that in many areas the highest hydraulic head is in Unit B of the Shakopee Formation and units A and B in the lowermost part of the St Peter Sandstone. See Figure1 for location of wells.

APPENDIX A

Spreadsheet with summary of borehole geophysical logging in the Lake Elmo study area.

Explanation of columns

A- Street address where tested well was located
B- Land surface elevation at well site
C- Depth in feet to static water level
D- Unique well number
E- Date of geophysical logging
F- Total well depth in feet
G- Depth in feet to bottom of well casing
H- Elevation of static water level
I- Stratigraphic interpretation
J- Stratigraphic interval exposed in open hole interval. Os=St Peter Sandstone, Op=Prairie du Chien Group, Shakopee Formation, QUAT=Quaternary glacial deposits. See Figure 2 for additional subdivisions A-F. Aquifer designations in parentheses indicates greater degree of uncertainty.
K- Date of flowlogging
L- Depth in feet where multi-parameter or flowlogs indicated flow through fractures. DI=data insufficient to interpret. NN=None noted
M- Depth in feet where caliper logs indicated presence of fractures or solution cavities. Only relatively sharp, pronounced deflections were demarked. Based on comparison of caliper logs to video logs this method likely underestimates number of bedding plane fractures (e.g. see Figure 3) because many fractures with narrow (<1 inch) apertures are not clearly demarked on caliper log signature. DI=data insufficient to interpret. NN=None noted
N- Comments

								APPENDIX A					
A	B	C	D	E	F	G	H	I	J	K	L	M	N
Address	elev	swl depth	Unique Well No.	Gamma Logged	Well Depth	casing depth	swl elev	stratigraphic interpretation	aquifer	Flow Logged	Flow indicated by logs (depth in feet)	Fractures indicated on caliper log (depth in feet)	comments
2819 IVY AVE N	909	17	110523	6/20/2007	93	92	892	0-49Q, 49-90OSTP, 90-bot OPDC	(OpB)	--	DI	93	
9198 31ST ST N	915	32	257572	9/20/2007	79	79	883	0-53? Q, 53-bot OSTP	(OsA)	--	DI	DI	**gamma only**
9046 31ST ST N	923	34	257275	3/31/2007	82	82?	889	0-74Q, 74-bot ?OSTP	(OsB)	--	DI	DI	standard gamma log only for this well
9202 31ST ST N	915	8	257418	6/5/2007	31	31	907	0-botQ	(QUAT)	--	DI	DI	2" screened well: gamma log only
9343 31ST ST N	923	29	257151	1/23/2007	60	60?	894	0-bot, ALL Q?	(QUAT)	--	DI	DI	
2959 JAMLEY AVE N	928	37	257411	5/25/2007	50	?50	891	0-bot Q	(QUAT)	--	DI	DI	gamma only
3023 JAMELY AVE N	932	18	257373	4/27/2007	64	64+	914	0-bot Q	(QUAT)	--	DI	DI	gamma only
9260 31ST ST N	918	25	616698	1/23/2007	100	90	893	0-90 Q, 90-bot OPDC	Op(B)	--	94	92, 95, 97, 99	
8555 27TH St N	991	101	670740	2/12/2007	239	226	890	0-19 Q, 19-32 OPVL, 32-39 OGWD, 39-198 OSTP, 198-bot OPDC	OpA	--	NN	232	
8605 27TH St N	987	101	670739	2/12/2007	240	225	886	0-23 Q, 23-31 OPVL, 31-37 OGWD, 37-197 OSTP, 197-bot OPDC	OpA	--	226, 238	225, 227, 231	
2816 INWOOD AVE N	972	80	437308	1/24/2007	210	209	892	0-72 Q, 72-186 OSTP, 186-bot OPDC	OpA	--	DI	DI	
2856 INWOOD AVE N	968	74	440560	1/24/2007	212	210	894	0-86 Q, 86-179 OSTP, 179-bot OPDC	OpA	--	DI	DI	caliper log error, no curve recorded
HWY 5 Office park	923	31	670792	5/23/2007	153	149	892	0-86Q, 86-144 OSTP, 144-bot OPDC	OpA		150	152	
9148 31ST ST N	925	24	257198	2/28/2007	139	97	901	0-49 Q, 49-82 OSTP, 82-bot OPDC	OpA-B	3/12/2007	119, 122, 131, 135	99, 110, 113, 122, 131, 139	
2895 IMPERIAL AVE N	965	80	585145	2/21/2007	219	206	885	0-34Q, 34-190 OSTP, 190-bot OPDC	OpA-B	--	208, 212, 215	207	
8226 26TH ST N	1010	126	670763	2/26/2007	260	231	884	0-52Q, 52-66 OPVL, 66-74 OGWD, 74-230 OSTP, 230-botOPDC	OpA-B	3/12/2007	235, 239	232, 234, 250, 258	
8715 27TH St N	992	102	257167	2/1/2007	228	196	890	0-14 Q, 14-22 OPVL, 22-29 OGWD, 29-187 OSTP, 187-bot OPDC	OpA-B	--	203, 223	200, 209	**gamma log only**
8875 27TH St N	945	59	257197	2/27/2007	169	145	886	0-50 Q, 50-130 OSTP, 130-bot OPDC	OpA-B	--	NN	146, 150, 153, 158, 160, 165	
9077 31ST ST N	931	43	604274	1/23/2007	133	110	888	0-55 Q, 55-110 OSTP, 110-bot OPDC	OpA-B		114, 129	115, 118, 121, 126, 129	
2696 IMPERIAL AVE N	992	103	617699	2/26/2007	241	222	889	0-39Q, 39-45 OPVL, 45-52 OGWD, 52-210 OSTP, 210-bot OPDC	OpA-B	--	NN	238	
2850 IMPERIAL AVE N	978	86	588139	2/21/2007	220	204	892	0-22 Q, 22-28 OPVL, 28-35 OGWD, 35-193 OSTP, 193-bot OPDC	OpA-B	--	214, 217, 219	NN	
8520 IRONWOOD Tr N	968	80	257152	1/25/2007	207	177	888	0-36Q, 36-173 OSTP, 173-bot OPDC	OpA-B	--	NN	183, 198, 203	
8540 IRONWOOD Tr N	977	92	257153	1/25/2007	214	190	885	0-17Q, 17-22 OPVL, 22-28 OGWD, 28-186 OSTP, 186-bot OPDC	OpA-B	--	209, 212	NN	
8560 IRONWOOD Tr N	981	95	424136	1/25/2007	209	195	886	0-16Q, 16-25 OPVL, 25-31 OGWD, 31-187 OSTP, 187-bot OPDC	OpA-B	--	NN	204	
8722 IRONWOOD Tr N	981	94	110434	1/30/2007	214	186	887	0-14Q, 14-18 OPVL, 18-25 OGWD, 25-181 OSTP, 181-bot OPDC	OpA-B	--	208	190, 192, 201, 204	**Unable to pull pump--must dig up**
8772 IRONWOOD Tr N	987	96	257194	2/23/2007	220	186	891	0-13Q, 13-21 OPVl, 21-27 OGWD, 27-184 OSTP, 184-bot OPDC	OpA-B	--	195, 203, 211, 215	187, 192, 201, 204, 207, 213, 218, 220	
2751 JAMLEY AVE N	912	26	257368	4/27/2007	116	96	886	0-31Q, 31-95 OSTP, 95-116 OPDC	OpA-B	5/8/2007	102?, 107?	97, 100, 102, 114	
2805 JAMLEY AVE N	918	29	451602	2/27/2007	127	110	889	0-18Q, 18-99 OSTP, 99-bot OPDC	OpA-B	--	116, 123, 126	116	
2877 JAMLEY AVE N	926	32	257371	4/27/2007	141	110	894	0-49Q, 49-104 OSTP, 104-bot OPDC	OpA-B	--	114, 120	114, 130	
2994 JAMLEY AVE N	928	37	604259	2/28/2007	142	103	891	0-59 Q, 59-98 OSTP, 98-bot OPDC	OpA-B		126, 136	105, 108, 111, 112, 114, 122, 126, 129, 133, 134, 140	
3052 JAMLEY AVE N	930	43	208450	2/28/2007	142	110	887	0-74 Q, 74-?102 OSTP, ?102-bot OPDC	OpA-B	5/8/2007	112, 120, 140, 143	112, 122, 124, 128, 131, 132, 137	
3053 JAMLEY AVE N	928	37	413551	2/19/2007	119	105	891	0-73 Q, 73-98 OSTP, 98-bot OPDC	OpA-B	--	107, 112	113	
8628 IRONWOOD Tr N	985	96	257154	1/25/2007	215	190	889	0-14Q, 14-23 OPVL, 23-30 OGWD, 30-190 OSTP, 190-bot OPDC	OpA-B (OsA)		192, 210	192, 209, 214	
8707 STILLWATER Blv N	939	51	257423	6/7/2007	165	138	888	0-33Q, 33-138 OSTP, 138-bot OPDC	OpA-B (OsA)	--	NN	NN	
8650 27TH St N	993	103	257170	2/12/2007	215	196	890	0-24 Q, 24-30 OPVL, 30-36 OGWD, 36-195 OSTP, 195-bot OPDC	OpB	--	213	NN	
9079 28TH St N	909	23	257281	3/31/2007	100	98	887	0-69 Q, 69-96 OSTP, 96-bot OPDC	OpB	--	DI	97, 99	
3036 INWOOD CT N	950	57	613401	2/22/2007	177	152	893	0-58Q, 58-151 OSTP, 151-bot OPDC	OpB	5/15/2007	152, 161, 171, 174, 175	157	
8549 IRONWOOD Tr N	981	97	257571	9/20/2007	201	190	884	0-20 Q, 20-25 OPVL, 25-32 OGWD, 32-192 OSTP, 192-bot OPDC	OpB	--	DI	DI	**gamma only**

2991 JAMLEY AVE N	930	51	257434	6/15/2007	111	107?	879	0-74Q, 74-104 OSTP; 104-bot OPDC	OpB	--	DI	DI	gamma only
HWY 5 Office park	920	30	710055	5/23/2007	108	107	890	0-42Q, 42-107 OSTP, 107-bot OPDC	OpB		DI	DI	
8310 27TH St N	977	91	196939	2/13/2007	220	200	886	0-22 Q, 22-26 OPVL, 26-33 OGWD, 33-?187 OSTP, ?187-bot OPDC	OpB (OsA)	5/8/2007	201, 204, 206, 207	200, 204, 206, 209, 212, 217	
9043 28TH St N	905	16	446288	2/27/2007	104	85	889	0-65 Q, 65-85 OSTP, 85-bot OPDC	OpB (OsA)	3/12/2007	90, 94, 99, 102	86, 87, 90, 94, 97, 98, 99, 102	
9049 28TH St N	908	20	257280	3/31/2007	108	89	889	0-?63Q, ?63-89 OSTP, 89-bot OPDC	OpB (OsA)	--	96	94, 106	
2809 JAMLEY AVE N	919	30	257370	4/27/2007	103	99	889	0-44Q, 44-99 OSTP, 99-bot OPDC	OpB (OsA)	--	DI	102	
2850 JAMLEY AVE N	915	24	493576	2/27/2007	94	?92	891	0-55Q, 55-92 OSTP, 92-bot OPDC	OpB (OsA)	--	DI	DI	
8620 STILLWATER Blv N	938	58	558222	5/25/2007	153	147	880	0-95 Q, 95-146 OSTP, 146-bot OPDC	OpB (OsA)	--	151	147	
HWY 5 Office park	930	36	710147	5/23/2007	127	120	894	0-?52 Q, ?52-120 OSTP, 120-bot OPDC	OpB (OsA)		122	125	
8652 IRONWOOD Tr N	985	95	257156	1/25/2007	197	135	890	0-11Q, 11-20 OPVL, 20-28 OGWD, 28-183 OSTP, 183-bot OPDC	OpB OsA	--	143	138, 143, 150, 158, 160, 171, 173	
8925 27TH St N	933	45	173927	9/15/2006	118	117	888	0-55Q, 55-bot OSTP	Os (B-C)	--	DI	DI	Gamma log only: WELL SEALED BY SAMPSON BROS. WELL CO.
8830 27TH St Ct N	950	66	162931	2/16/2007	151	?147	884	0-28 Q, 28-bot OSTP, (see comments)	Os(A)	--	DI	DI	did not reach bot. driller picked opdc at 127'
8702 IRONWOOD Tr N	980	93	257408	5/25/2007	181	180?	887	0-15Q, 15-25 OPGW, 25-bot OSTP	Os(A)	--	DI	180	
2904 JAMLEY AVE N	913	24	257372	4/27/2007	96	?94	889	0-45 Q, 45-bot OSTP	Os(A)	--	DI	Di	
Lake Elmo Park Reserve 5X	945	?	257569	9/17/2007	93	75?	?	0-20 Q, 20-bot OSTP	Os(A)		DI	NN	**Gamma and caliper logs only**
8657 IRONWOOD Tr N	988	96	257365	4/27/2007	157	157+?	892	0-11 Q, 11-25 OPVL, 25-30 OGWD, 30-bot OSTP	Os(C)	--	DI	DI	
8690 IRONWOOD Tr N	981	95	257193	2/23/2007	130	130+?	886	0-16Q, 16-20 OPVL, 20-26 OGWD, 26-bot OSTP	Os(D)	--	DI	DI	
8633 IRONWOOD Tr N	986	95	257155	1/25/2007	183	182	891	0-15Q, 15-23 OPVL, 23-30 OGWD, 30-bot OSTP	OsA	--	DI	DI	
2940 JAMLEY AVE N	921	29	257437	6/20/2007	46	46?	892	0-40Q, 40-bot OSTP	OsA	--	DI	DI	gamma only
2991 JAMLEY AVE N	930	45	257436	10/4/2007	102	102	885	0-55 Q, 55-bot OSTP	OsA		DI	DI	gamma only; 2 inch well
2990 JANERO AVE N	926	42	257501	10/22/2007	105	83?	884	0-51 Q, 51-bot. OSTP	OsA	--	DI	DI	Gamma only
8364 STILLWATER Blv N	962	70	599973	1/22/2007	167	160	892	0-77 Q, 77-bot OSTP	OsA	--	NN	166	
Lake Elmo Park Reserve old 5 inch	904	25	257574	10/12/2007	80	69	879	0-22 Q, 22-80 bot OSTP	OsA		DI	DI	**Gamma log only**
Lake Elmo Park Reserve 5 inch	917	43	257568	9/17/2007	90	69	874	0-21 Q, 21-bot. OSTP	OsA		73	70, 72, 75, 78, 81, 83, 84, 88	
Lake Elmo Park Reserve 4 inch	904	21	257567	9/17/2007	81	70	883	0-13 Q, 13-bot. OSTP	OsA		NN	72, 76, 80	
8244 27TH St N	984	98	511739	2/13/2007	213	211	886	0-35 Q, 35-39 OPVL, 39-46 OGWD, 46-Bot OSTP	OsA (Op B)	--	DI	DI	
8840 27TH St Ct N	950	67	187000	2/16/2007	156	154?	883	0-27 Q, 27-bot OSTP	OsA (OpB)	--	DI	DI	
8643 28TH St N	993	101	257160	2/1/2007	196	192	892	0-8Q, 8-26 OPVL, 26-36 OGWD, 36-bot OSTP (possible OPDC top at 193?)	OsA (OpB)	--	DI	193	
HWY 5 Office park	930	33	733001	5/23/2007	120	118	897	0-48 Q, 48-bot OSTP	OsA (OpB)		DI	118	
8845 27TH St N	950	68.5	174267	2/12/2007	170	147	882	0-36 Q, 36-161 OSTP, 161-bot OPDC	OsA OpB	--	NN	150, 154, 168	
2890 IMPERIAL AVE N	968	81	575148	2/21/2007	220	185	887	0-66Q, 66-197 OSTP, 197-bot OPDC	OsA OpAB	3/9/2007	186, 188, 196, 202, 204, 216	196	
8364 26TH ST N	1004	121	588140	2/27/2007	253	223	883	0-40Q, 40-59OPVL, 59-65 OGWD, 65-227 OSTP, 227-bot OPDC	OsA OpA-B	3/12/2007	227	225, 243	
9155 28TH St N	915	30	257374	4/27/2007	129	103	885	0-32Q, 32-104 OSTP, 104-bot OPDC	OsA OpA-B	--	125	106, 109, 120, 125	
9018 31ST ST N	925	34	670770	1/23/2007	134	102	891	0-73 Q, 73-104 OSTP, 104-bot OPDC	OsA OpA-B	--	129	102, 125, 129	
8655 27TH St N	994	109	257171	2/12/2007	209	188	885	0-14 Q, 14-35 OPVL, 35-41 OGWD, 41-200 OSTP, 200-bot OPDC	OsA OpB	5/8/2007	194, 199, 208	191, 194, 197, 202, 208	
8860 27TH St Ct N	957	70.5	182731	2/16/2007	165	147	887	0-48 Q, 48-148 OSTP, 148-bot OPDC	OsA OpB		160	148	
2618 IMPERIAL AVE N	1012	123	569782	2/26/2007	237	225	889	0-48Q, 48-67 OPVL, 67-74 OGWD, 74-230 OSTP, 230-bot OPDC	OsA OpB	--	NN	226, 228	
2678 IMPERIAL AVE N	1000	110	607488	2/20/2007	238	222	890	0-40 Q, 40-55 OPVL, 55-61 OGWD, 61-224 OSTP, 224-bot OPDC	OsA OpB	--	NN	222	
2699 IMPERIAL AVE N	997	107	678196	2/26/2007	239	209	890	0-32Q, 32-47 OPVL, 47-53 OGWD, 53-210 OSTP, 210-bot OPDC	OsA OpB	3/9/2007	212, 230, 237	230, 238	
2906 INNSDALE AVE N	969	77	440566	2/19/2007	184	175	892	0-55 Q, 55-180 OSTP, 180-bot OPDC	OsA OpB	--	182	174	
2960 INNSDALE AVE N	963	72	471065	2/19/2007	173	159	891	0-85 or 0-94 Q, 85- or 94-168 OSTP, 168-bot OPDC?	OsA OpB	--	162, 168, 172	162, 169, 172	
8580 IRONWOOD Tr N	984	96	447248	1/25/2007	214	193	888	0-24Q, 24-34 OPVL, 34-39 OGWD, 39-194 OSTP, 194-bot OPDC	OsA OpB	--	196	193	
2798 JAMLEY AVE N	918	29	257369	4/27/2007	104	101	889	0-39 Q, 39-102 OSTP, ?102-bot ?OPDC	OsA OpB	--	102?	102	
2970 JAMLEY AVE N	922	35	257412	5/25/2007	121	105	887	0-43Q, 43-107 OSTP, 107-bot OPDC	OsA OpB	--	106, 110, 117	106, 108, 110, 114, 116	
8483 27TH St N	990	98	453250	1/31/2007	187	175	892	0-14Q, 14-32 OPVL, 32-38 OGWD, 38-bot OSTP	OsA-B	--	183	183, 186	

8905 27TH St N	940	53	257172	2/13/2007	128	111	887	0-21 Q, 21-bot OSTP	OsA-B	--	NN	127	
8780 27TH St Ct N	968	79	257185	2/22/2007	157	147	889	0-16Q, 16-82 OSTP (weathered/reworked?) 82-bot OSTP	OsA-B	--	NN	148, 153	
8800 27TH St Ct N	949	80	182679	2/16/2007	157	150	869	0-25 Q, 25-bot OSTP	OsA-B	--	NN	154	
2876 INNSDALE AVE N	971	76	257405	5/23/2007	167	156	895	0-40 Q, 40-bot OSTP	OsA-B	--	159, 165, 167	162	
2965 INNSDALE AVE N	969	73	257181	2/19/2007	167	148?	896	0-82 Q, 82-bot OSTP	OsA-B	--	152, 162	167	
3077 INWOOD CT N	925	36	687850	2/22/2007	125	112	889	0-62Q, 62-bot OSTP	OsA-B	--	115, 118, 121, 124	115, 118, 122, 124, 126, 128	
3014 JAMLEY AVE N	930	43	536672	2/19/2007	97	90	887	0-57 Q, 57-bot OSTP	OsA-B	--	NN	91, 93, 95	
8268 STILLWATER Blv N	938	42	634270	1/22/2007	138	126	896	0-37 Q, 37-bot OSTP	OsA-B	--	NN	NN	
8623 28TH St N	991	102	257161	2/1/2007	217	177	890	0-19Q, 19-28 OPVL, 28-37 OGWD, 37-194 OSTP, 194-bot OPDC	OsA-B OpB	--	184, 189, 209	180, 185, 189, 194, 198, 205, 213	
2915 INWOOD AVE N	953	63	154443	1/31/2007	165	145	890	0-50Q, 50-161 OSTP, 161-bot OPDC	OsA-B OpB	5/8/2007	155, 158	150, 153, 155, 157	
8282 27TH St N	977	89	465954	2/13/2007	187	157	888	0-48 Q, 48-bot OSTP	OsA-C	--	NN	158, 163, 167, 173, 178, 183, 187	
8478 27TH St N	981	96	503288	1/31/2007	187	168	885	0-26Q, 26-28 OPGW, 28-34 OGWD, 34-bot OSTP	OsA-C	--	175	170, 175, 179, 184	
8570 27TH St N	988	101	700594	2/27/2007	197	154	887	0-?31 Q, ?31-34 OPVL, 34-39 OGWD, 39-bot OSTP	OsA-C	--	188	164, 174, 182, 189, 191, 193, 194, 196	
8656 27TH St N	994	105	257375	4/27/2007	189	154	889	0-12Q, 12-30 OPVL, 30-36 OGWD, 36-bot OSTP	OsA-C	5/8/2007	176, 180	170, 176, 185	
8810 27TH St Ct N	937	64	173925	2/16/2007	146	116	873	0-34 Q, 34-bot OSTP	OsA-C	--	121, 144	118, 124, 126, 128, 137, 139, 140, 142, 143	
8820 27TH St Ct N	949	66	185945	2/16/2007	137	114	883	0-22 Q, 22-bot OSTP	OsA-C	--	124, 130	118, 124	
2811 IMPERIAL AVE N	980	91	598819	2/21/2007	196	169	889	0-28Q, 28-33 OPVL?, 33-41 OGWD, 41-bot OSTP	OsA-C	--	176, 186	176, 194	
2841 IMPERIAL AVE N	978	87	576160	2/21/2007	193	157	891	0-28Q, 28-31 OPVL?, 31-38 OGWD, 38-bot OSTP	OsA-C	--	163, 184, 191	163, 192	
2621 INNSDALE AVE N	997	104	257173	2/13/2007	198	171	893	0-30? Q, ?30-38 OPVL, 38-45 OGWD, 45-bot OSTP	OsA-C	--	NN	171, 194, 195, 196, 199	
2895 INNSDALE AVE N	969	78	257182	2/19/2007	177	149	891	0-33 Q, 33-bot OSTP	OsA-C	--	155, 160, 174	153, 174	
2773 INWOOD AVE	981	93	257442	6/25/2007	182	161	888	0-25Q, 25-31 OGWD, 31-bot OSTP	OsA-C	--	DI	DI	gamma only
3033 INWOOD CT N	955	59	622211	2/22/2007	150	127	896	0-74Q, 74-bot OSTP	OsA-C	3/9/2007	128, 130	129, 133, 138, 145, 148, 150	
8748 IRONWOOD Tr N	981	96	257410	5/25/2007	177	145	885	0-16Q, 16-19 ?OPVL?, 19-26 OGWD, 26-bot OSTP	OsA-C	--	146, 163, 169, 173	146, 150, 155, 160, 163, 169, 173	
8780 IRONWOOD Tr N	991	98	257163	1/31/2007	188	151	893	0-7Q, 7-21 OPVL, 21-27 OGWD, 27-bot OSTP	OsA-C	--	176	160, 166, 175, 177, 180, 184	
8785 IRONWOOD Tr N	992	102	257164	1/31/2007	183	154	890	0-9Q, 9-26 OPVL, 26-32 OGWD, 32-bot OSTP	OsA-C	--	NN	167, 172, 175, 178, 182	
8384 STILLWATER Blv N	958	70	257277	3/31/2007	158	138	888	0-84Q, 84-bot OSTP	OsA-C	--	140, 145, 150	144, 146	
8643 STILLWATER Blv N	938	48	676479	1/23/2007	140	100	890	0-40 Q, 40-bot OSTP	OsA-C	--	NN	99, 102, 105, 116, 119, 135, 140	
8680 STILLWATER Blv N	931	48	583343	1/23/2007	134	106	883	0-59 Q, 59-bot OSTP	OsA-C	5/9/2007	136	105, 108, 110, 113, 115, 124, 136	
2770 IRISH Ave N	991	99	671999	2/23/2007	213	159	892	0-15Q, 15-30 OPVL, 30-35 OGWD, 35-195 OSTP, 195-bot OPDC	OsA-C OpB	3/12/2007	160, 178, 185, 210, 213	160, 170, 185, 190, 193, 203, 210	
8284 26TH ST N	1010	122	577037	5/23/2007	216	170	888	0-47Q, 47-60OPVL, 60-67 OGWD, 67-bot OSTP	OsA-D	--	178, 212, 214	171, 174, 179, 210	
8815 27TH St N	957	71	176036	2/12/2007	142	?99	886	0-?15 Q, ?15-bot OSTP	OsA-D	--	DI	DI	**logged only to 83'**
8648 28TH St N	991	101	257435	6/20/2007	185	145	890	0-21Q, 21-29OPVL, 29-35OGWD, 35-bot OSTP	OsA-D	--	DI	DI	Gamma log only
2655 IMPERIAL AVE N	1006	114	569982	2/21/2007	214	172	892	0-41Q, 41-57 OPVL, 57-65 OGWD, 65-bot OSTP	OsA-D	--	177, 180, 209	214	
2656 IMPERIAL AVE N	1009	116	554316	3/13/2007	222	170	893	0-42Q, 42-62 OPVL, 62-68 OGWD, 68-bot OSTP	OsA-D	--	173, 180, 200, 218	180	
8154 26TH ST N	1010	120	616945	5/25/2007	224	158	890	0-65 Q, 65-70 OGWD, 70-bot OSTP	OsA-E	--	173, 188	161, 163, 165, 167, 170, 177, 182, 188, 193, 204, 212, 217, 223	
2760 IMPERIAL AVE N	988	98	609537	2/20/2007	200	127	890	0-22 Q, 22-42 OPVL, 42-49 OGWD, 49-bot OSTP	OsA-F	5/22/2007	152, 170, 180, 198	video log: 128, 147, 155, 160, 171, 178, 182, 192	
2769 IMPERIAL AVE N	992	98	614269	2/20/2007	197	123	894	0-33 Q, 33-41 OPVL, 41-46 OGWD, 46-bot OSTP	OsA-F	2/20/2007	128, 140, 160, 162, 180, 192, 197	140, 148, 156, 160, 171, 179, 181, 184	
8282 STILLWATER Blv N	945	59	154476	1/24/2007	158	80	886	0-70 Q, 70-bot OSTP	OsA-F	5/15/2007	81?, 157, 159?	video log: 117, 128, 129, 139, 157, 159, 160	
2759 IRISH Ave N	992	100	257191	2/23/2007	199	187	892	0-15Q, 15-29 OPVL, 29-35 OGWD, 35-191 OSTP, 191-bot OPDC	OsAOpB	--	NN	190, 195	
3010 JANERO AVE N	931	43	257279	3/31/2007	108	?102	888	0-56Q, 56-104 OSTP, 104-bot OPDC	OsAOpB	--	103, 107	103, 107	
8341 27TH St N	984	94	442140	2/13/2007	172	168	890	0-21 Q, 21-29 OPVL, 29-36 OGWD, 36-bot OSTP	OsB	--	DI	NN	
8352 27TH St N	989	92	447253	2/13/2007	176	169	897	0-18 Q, 18-30 OPVL, 30-35 OGWD, 35-bot OSTP	OsB	--	DI	170	
8639 27TH St N	994	109	257409	5/25/2007	183	174	885	0-?19 Q, ?19-35 OPVL, 35-42 OGWD, 42-bot OSTP	OsB	--	179	173, 176, 177, 180	
8735 27TH St N	988	98.5	415659	2/1/2007	165	163	890	0-15Q, 15-19 OPVL, 19-27 OGWD, 27-bot OSTP	OsB	--	DI	NN	
9078 31ST ST N	921	34	257150	1/23/2007	90	87?	888	0-47 Q, 47-bot OSTP	OsB	--	DI	DI	
9141 31ST ST N	920	28	257274	3/31/2007	82	78	892	0-38Q, 38-bot OSTP	OsB	--	NN	82	
2935 INNSDALE AVE N	969	73	428478	2/19/2007	161	148	896	0-73 Q, 73-bot OSTP	OsB	--	151, 155	162, 165	

8716 IRONWOOD Tr N	978	93	257366	4/27/2007	161	151	885	0-12Q, 12-19 OPVL, 19-24 OGWD, 24-bot OSTP	OsB	--	155, 159	158, 159	
2909 JAMLEY AVE N	926	35	257413	5/25/2007	92	87	891	0-47Q, 47-bot OSTP	OsB	--	90	89, 91	
8863 STILLWATER Blv N	934	48	257278	3/31/2007	115	?108	886	0-76 Q, 76-bot OSTP	OsB	--	111, 115	109, 113, 115	
8866 STILLWATER Blv N	931	48	257149	1/23/2007	122	121?	883	0-74 Q, 74-bot OSTP	OsB	--	DI	DI	
8454 26TH ST N	1005	117	582669	2/26/2007	197	169	888	0-?36Q, ?36-50 OPVL, 50-56 OGWD, 56-bot OSTP	OsB-C	--	175	170, 191	
8375 27TH St N	992	98	440577	1/31/2007	171	167	894	0-16Q, 16-33 OPVL, 33-39 OGWD, 39-bot OSTP	OsB-C	--	DI	NN	
8623 27TH St N	990	104	679966	2/12/2007	176	154	886	0-14 Q, 14-33 OPVL?, 33-39 OGWD, 39-bot OSTP	OsB-C	--	174	154, 159, 163, 173	
8785 27TH St N	965	82.5	194159	2/1/2007	153	134	883	0-22Q, 22-bot OSTP	OsB-C	--	147	137, 151	
8920 27TH St N	933	48	121056	4/27/2007	108	93	885	0-43Q, 43-bot OSTP	OsB-C	--	95, 102	93, 96, 98, 102, 104, 106, 108	
8850 27TH St Ct N	951	69	173938	2/16/2007	126	106	882	0-30 Q, 30-bot OSTP	OsB-C	--	NN	113, 116, 125	
2626 INNSDALE AVE N	998	107	519084	5/23/2007	188	174	891	0-25Q, 25-41 OPVL, 41-47 OGWD, 47-bot OSTP	OsB-C	6/8/2007	174, 180	176, 180, 183	
2796 INWOOD AVE	976	84	428479	1/24/2007	162	146	892	0-15 Q, 15-20 OPVL, 20-26 OGWD, 26-bot OSTP	OsB-C	--	NN	147, 151, 156	
2875 INWOOD AVE	960	72	121060	1/24/2007	151	126	888	0-40 Q, 40-bot OSTP	OsB-C	--	130, 144	138, 144, 146	
3082 INWOOD CT N	952	64	569744	2/22/2007	133	121	888	0-77Q, 77-bot OSTP	OsB-C	5/15/2007	121, 126, 130, 133	122, 127, 130	
8618 IRONWOOD Tr N	980	94	257424	6/7/2007	172	158	886	0-40Q, 40-bot OSTP	OsB-C	--	159, 162, 164	162, 164, 165, 170	
8725 IRONWOOD Tr N	988	97	257165	1/30/2007	176	155	891	0-16Q, 16-21 OPVL, 21-30 OGWD, 30-bot OSTP	OsB-C		164, 168, 171	159, 164, 168, 173	
8255 STILLWATER Blv N	949	62	257143	1/22/2007	150	121	887	0-60 Q, 60-bot OSTP	OsB-C	--	125, 128	130, 141	
8404 STILLWATER Blv N	958	72	257145	1/22/2007	145	126	886	0-86 Q, 86-bot OSTP	OsB-C	--	130, 143	132, 137, 144	
8464 STILLWATER Blv N	954	65	257362	4/27/2007	136	121	889	0-78 Q, 78-bot OSTP	OsB-C	--	124, 127	129	
8740 STILLWATER Blv N	938	44	257148	4/18/2007	109	?93	894	0-70 Q, 70-bot OSTP	OsB-C	--	DI	97, 108	**Gamma log and caliper log only**
8367 26TH ST N	1015	131	569984	3/13/2007	216	174	884	0-51 Q, 51-60 OPVL, 60-68 OGWD, 68-bot OSTP	OsB-D	--	177, 208	181, 187, 198	
8457 26TH ST N	1018	129	587849	2/27/2007	208	170	889	0-42Q, 42-64 OPVL, 64-70 OGWD, 70-bot OSTP	OsB-D	--	NN	171, 174, 177, 179, 180, 182, 183, 186, 205	
8755 27TH St N	971	82.5	176046	2/12/2007	153	108	889	0-32 Q, 32-bot OSTP	OsB-D	--	114, 133	110, 114, 122, 129, 133, 139, 142, 145, 149	
8790 27TH St Ct N	970	80	176049	2/22/2007	141	109	890	0-16Q, 16-57 OSTP?(weathered?), 57-bot OSTP	OsB-D	--	127	111, 113, 117, 119, 123, 127, 129, 130, 131, 133, 137, 139, 142, 143, 144, 146	
2930 INNSDALE AVE N	966	74	257183	2/19/2007	157	128	892	0-78 Q, 78-bot OSTP	OsB-D	--	129, 138	129, 141	
8428 STILLWATER Blv N	959	70	257147	1/23/2007	146	110?	889	0-85 Q, 85- bot OSTP	OsB-D	--	126, 144	127, 128, 130, 134, 142, 144	
8215 26TH ST N	1022	134	598818	5/23/2007	216	170	888	0-60 Q, 60-74 OPVL, 74-81 OGWD, 81-bot OSTP	OsB-E	--	174, 194, 203, 210, 214	171, 194, 204	
2677 IMPERIAL AVE N	1000	107	606937	4/18/2007	193	150	893	0-35Q, 35-50 OPVL, 50-56 OGWD, 56-bot OSTP	OsB-E		162, 190	152, 154, 162, 164, 180, 190	
8165 26TH ST N	1021	131	554311	3/13/2007	218	139	890	0-56Q, 56-74 OPVL, 74-81 OGWD, 81-bot OSTP	OsB-F	--	169, 204	139, 146, 154, 163, 178, 186, 193	
8247 27TH St N	1001	105	457680	3/13/2007	177	167	896	0-28 Q, 28-44 OPVL, 44-51 OGWD, 51-bot OSTP	OsC	--	NN	175	
8685 27TH St N	994	107	257199	2/28/2007	155	152	888	0-23Q, 23-30 OPVL, 30-38 OGWD, 38-bot OSTP	OsC	--	DI	NN	
8687 28TH St N	987	99	257159	2/1/2007	154	152	888	0-8Q, 8-23 OPVL, 23-32 OGWD, 32-bot OSTP	OsC	--	DI	153	
2655 INNSDALE AVE N	994	101	453245	2/26/2007	171	169	893	0-15Q, 15-33 OPVL, 33-41 OGWD, 41-bot OSTP	OsC	--	DI	NN	
8659 STILLWATER Blv N	935	46	257363	4/27/2007	105	105	889	0-38Q, 38-bot OSTP	OsC	--	DI	DI	
8281 26TH ST N	1016	130	590036	2/23/2007	195	172	886	0-61Q, 61-69 OPVL, 69-75 OGWD, 75-bot OSTP	OsC-D	--	NN	180, 182, 188	
8301 27TH St N	982	96	440589	2/13/2007	160	147	886	0-21 Q, 21-33 OPVL (weathered?), 33-38 OGWD, 38-bot OSTP	OsC-D	--	NN	147, 152	
8770 27TH St Ct N	973	82	176020	2/22/2007	138	110	891	0-16Q, 16-88 OSTP (weathered/reworked?), 88-bot OSTP	OsC-D	--	128	110, 116, 121, 122, 128, 131, 133, 137	
2811 IRISH Ave N	987	96	257192	2/23/2007	158	134	891	0-20Q, 20-26 OPVL, 26-32 OGWD, 32-bot OSTP	OsC-D	--	135?, 140?, 145?, 152?	143, 145, 158	
8521 IRONWOOD Tr N	977	88	257299	4/18/2007	155	?132	889	0-25Q, 25-bot OSTP	OsC-D		143, 146, 149, 154	135, 138, 149	
8603 IRONWOOD Tr N	981	96	257276	3/31/2007	156	131	885	0-12 Q, 12-26 OPVL, 26-31 OGWD, 31-bot OSTP	OsC-D	--	132, 143	140, 143	
8674 IRONWOOD Tr N	985	95	257157	1/30/2007	140	136	890	0-14Q, 14-19OPVL, 19-28 OGWD, 28-bot OSTP	OsC-D	--	139	139	
8775 IRONWOOD Tr N	991	101	257162	1/31/2007	144	135	890	0-10 Q, 10-25 OPVL, 25-32 OGWD, 32-bot OSTP	OsC-D	--	138	140, 144	
8567 STILLWATER Blv N	944	57	257200	2/28/2007	105	100	887	0-38 Q, 38-bot OSTP	OsC-D	--	NN	102, 104, 107	
8119 26TH ST N	1018	129	577036	2/23/2007	209	169	889	0-64Q, 64-72 OPVL, 72-78 OGWD, 78-bot OSTP	OsC-E	--	NN	171, 173, 177, 191, 202, 208	
2580 IMPERIAL AVE N	1019	126	569978	3/13/2007	208	173	893	0-51 Q, 51-72 OPVL, 72-80 OGWD, 80-bot OSTP	OsC-E	--	180, 205	175, 177, 180, 203	
2528 IMPERIAL AVE N	1030	137	554312	2/20/2007	208	170	893	0-62 Q, 62-83 OPVL, 83-90 OGWD, 90-bot OSTP	OsC-F	2/20/2007	185, 198, 202, 207	170, 183, 187, 202	
2895 INWOOD AVE N	957	68	156421	1/24/2007	112	106	889	0-48 Q, 48-bot OSTP	OsD	--	NN	NN	
8511 STILLWATER Blv N	950	58	257430	6/14/2007	106	97	892	0-42Q, 42-bot OSTP	OsD	--	101, 104	104	
8644 27TH St N	991	102	257166	2/1/2007	134	119 or 133	889	0-12 Q, 12-30 OPVL, 30-38 OGWD, 38-bot OSTP	OsD-E	--	DI	DI	
8709 27TH St N	995	106	257565	8/22/2007	142	124??	889	0-14Q, 14-31 OPVL, 31-36 OGWD, 36-bot OSTP	OsD-E	--	DI	DI	**gamma log only**

8592 IRONWOOD Tr N	981	94	257364	4/27/2007	138	122	887	0-15Q, 15-30 OPVL, 30-36 OGWD, 36-bot OSTP	OsD-E	--	130	125, 138	**Unable to pull pump due to location of plumbing work.**
8308 STILLWATER Blv N	940	59	257144	1/22/2007	101	85	881	0-66 Q, 66-bot OSTP	OsD-F	--	90?	100	
2961 INWOOD AVE	950	61	257298	4/18/2007	89	83	889	0-60 Q, 60-bot OSTP	OsE	--	85	85	
2731 INWOOD AVE N	986	101	257367	4/27/2007	125	110	885	0-32Q, 32-37 OGWD, 37-bot OSTP	OsE-F	--	NN	113, 115, 118, 120, 123	
2793 INWOOD AVE	979	82	257195	2/26/2007	110	105?	897	0-32Q, 32-bot OSTP	OsE-F	--	NN	107, 109	
9065 28TH St N			257421	no log			0			--			unable to log: access issues
9038 31ST ST N			257419	no log			0			--			could not log
9051 31ST ST N			257438	**no log**			0			--			could not log
9066 31ST ST N			257439	**no log**			0			--			could not log
9095 31ST ST N			257432	no log			0			--			could not log
9098 31ST ST N			257440	no log			0			--			could not log
9181 31ST ST N			257420	no log			0			--			could not log
9240 31ST ST N			257433	no log			0			--			could not log
92XX 31ST ST N			no well	no well			0			--			no well at this site
9345 31ST ST N			257506	no log			0			--			could not log
9350 31ST ST N			257507	no log			0			--			could not log
8695 IRONWOOD Tr N			257428	no log			0			--			MGS: Unable to gamma log
2742 IVY AVE N			pending	pending			0			--			
2935 JAMLEY AVE N			257508	no log			0			--			could not log
3004 JAMLEY AVE N			pending	pending			0			--			
2950 JANERO AVE N			257427	no log			0			--			could not log
3030 JANERO AVE N			257282	**no log**			0			--			could not log
8488 STILLWATER Blv N			**pending**	pending			0			--			
8583 STILLWATER Blv N			257431	no log			0			--			**MGS: Unable to gamma log**
8627 STILLWATER Blv N			257441	no log			0			--			**could not log**

Appendix B

Fracture observations in downhole video logs

"narrow" refers to fractures with apertures that have maximum apertures of about one-quarter inch or less

"wide" refers to fractures with apertures that have a maximum aperture of greater than one-quarter inch

VF= Vertical or subvertical fracture

BPF= Bedding plane fracture (subhorizontal)

Numbers refer to depth in feet

8282 Stillwater Blvd. N. (Unique number 154476)

83.0 narrow BPF
83.5 narrow BPF
83.8 narrow BPF
83.9 narrow BPF
86.4 narrow BPF
87.7 narrow BPF
90.0 narrow BPF, with oxidized iron
90.3 narrow BPF, narrow VF
90.6 narrow BPF, narrow VF
92.0 narrow BPF
94.5 narrow BPF, narrow VF
97.4 narrow BPF
98.6 narrow BPF, narrow VF's
98.9 narrow BPF
99.5 narrow BPF, narrow VF's
100.1 narrow BPF
101.1 narrow BPF, narrow VF's
102.6 narrow BPF
102.8 narrow BPF
103.2 narrow BPF, narrow VF
104.0 narrow BPF
104.4 narrow BPF
104.5 narrow BPF
108.2 narrow BPF
108.6 narrow VF's in en echelon pattern
109.1 narrow BPF, narrow VF
111.0 narrow BPF
112.1 narrow BPF
112.4 narrow BPF
113.4 narrow BPF
114.0 narrow BPF
117.2 narrow BPFs
117.4 wide BPF, narrow VFs, with oxidized iron
118.6 narrow BPF
123.9 narrow BPF
125.0 narrow BPF
128.0 wide BPF, narrow VFs, with oxidized iron
128.2 wide BPF, narrow VFs, with oxidized iron
132.4 narrow BPF
133.3 narrow BPFs
138.0 narrow BPF, narrow VFs
144.0 narrow VFs
147.3 wide BPF
148.9 wide BPF
151.6 wide BPF
157.0 to 158.0 wide BPFs, cavernous

2760 Imperial Ave. N. (Unique number 609537)

127.2 wide BPF
130.1 narrow BPF
133.5 narrow BPF
134.6 narrow BPF
139.4 narrow BPF
143.8 narrow BPF
145.7 wide BPF, narrow VF
146.5 wide BPF
150.8 narrow BPF
152.7 narrow BPF
154.5 wide BPF
156.3 narrow BPF
159.8 wide BPF, narrow VFs to 159.1
160.3 narrow BPF
161.3 narrow BPF
166.0 narrow BPF, narrow VF
170.8 wide BPF, wide VF
179.1 wide BPF
180.1 narrow BPF
181.1 wide BPF
181.5 wide BPF
187.4 wide BPF
192.1 wide BPF, with oxidized iron

APPENDIX C

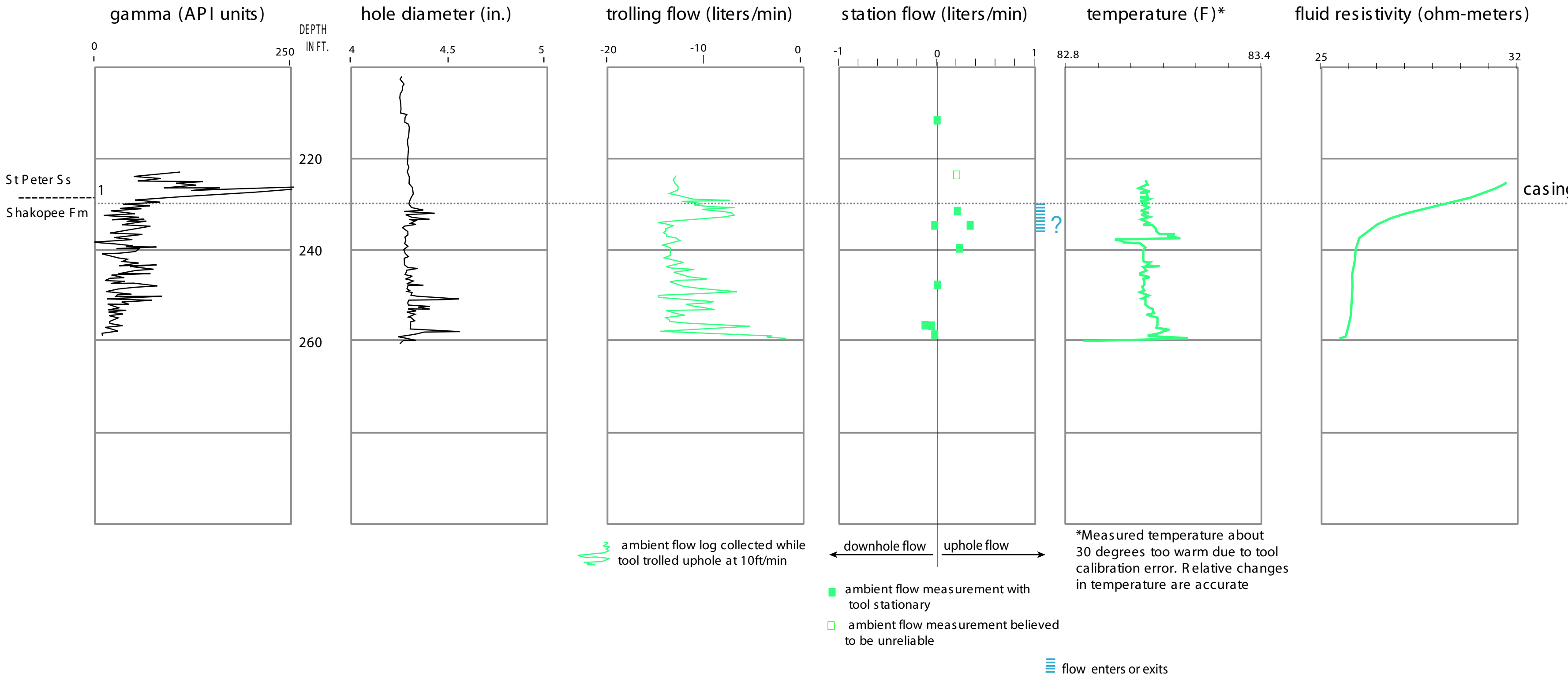
Illustrated summaries of flowmeter logging data from boreholes in the Lake Elmo study area. Locations of boreholes shown in Figure 1 of this report, and more complete locality, well construction, and stratigraphic information can be found in Appendix A and in County Well Index (CWI) maintained by the Minnesota Department of Health (MDH).

Numbers one through six in gamma column refer to fine clastic beds similarly numbered in Figure 2.Note that the position of aquitards on these illustrations corresponds to stratigraphic position of fine clastic or carbonate rock intervals that separate the most closely spaced inflow and outflow locations in the open borehole. See the text of this report, and Runkel and others (2003, 2006) for additional explanation of flowmeter logging procedures.

Abbreviations used in illustrations:

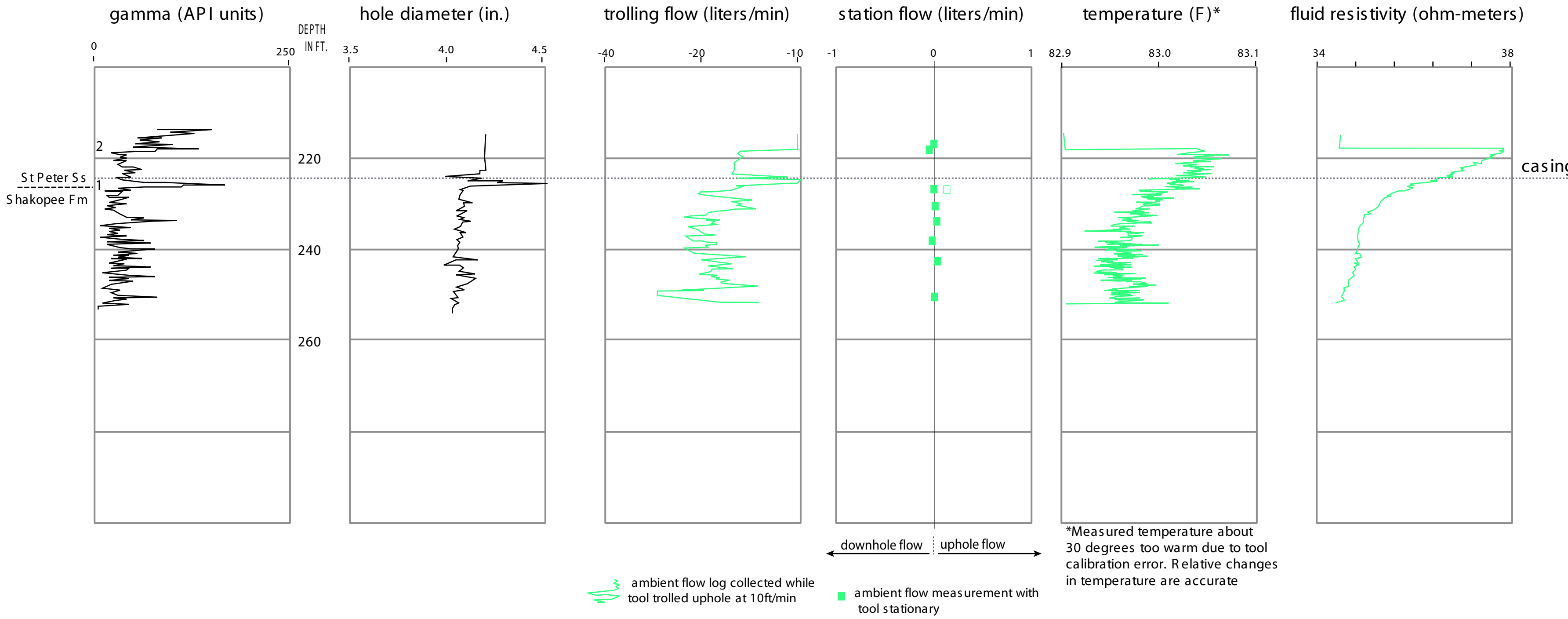
F (Fahrenheit)
gal (gallons)
in. (inches)
Ss (Sandstone)
Fm (Formation)
min (minute)
API (American Petroleum Institute) (standard scale for natural gamma activity)
BPF (bedding plane fracture)
FT (feet)

8226 26th St N (670763)



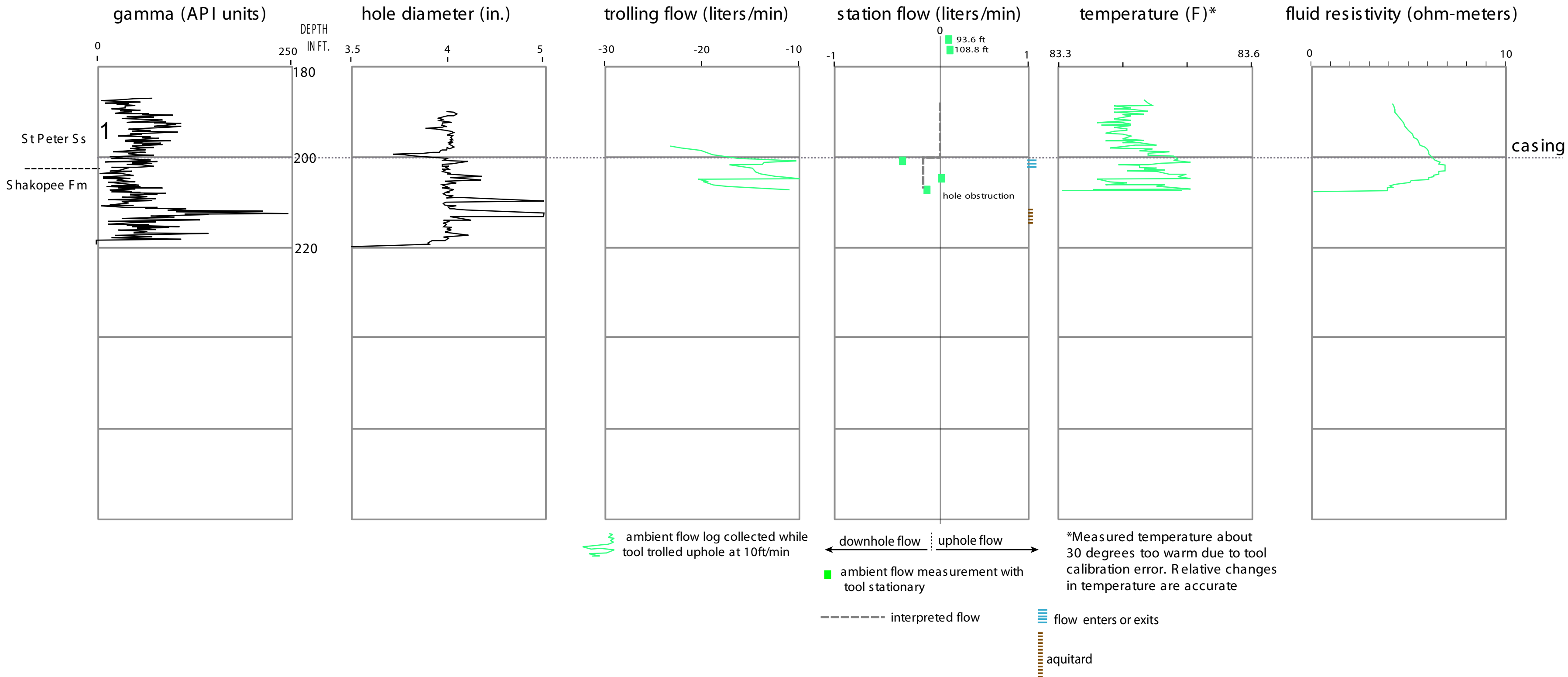
Interpretation overview: No consistent vertical flow measured. Shifts in temperature log, and low rates of apparent upflow from about 230 to 240 ft may be result of ephemeral upflow through fractures in this interval, or of cross-hole flow. The trolling log curve very closely matches the hole diameter, also indicating no measurable vertical flow.

8364 26th St N (588140)



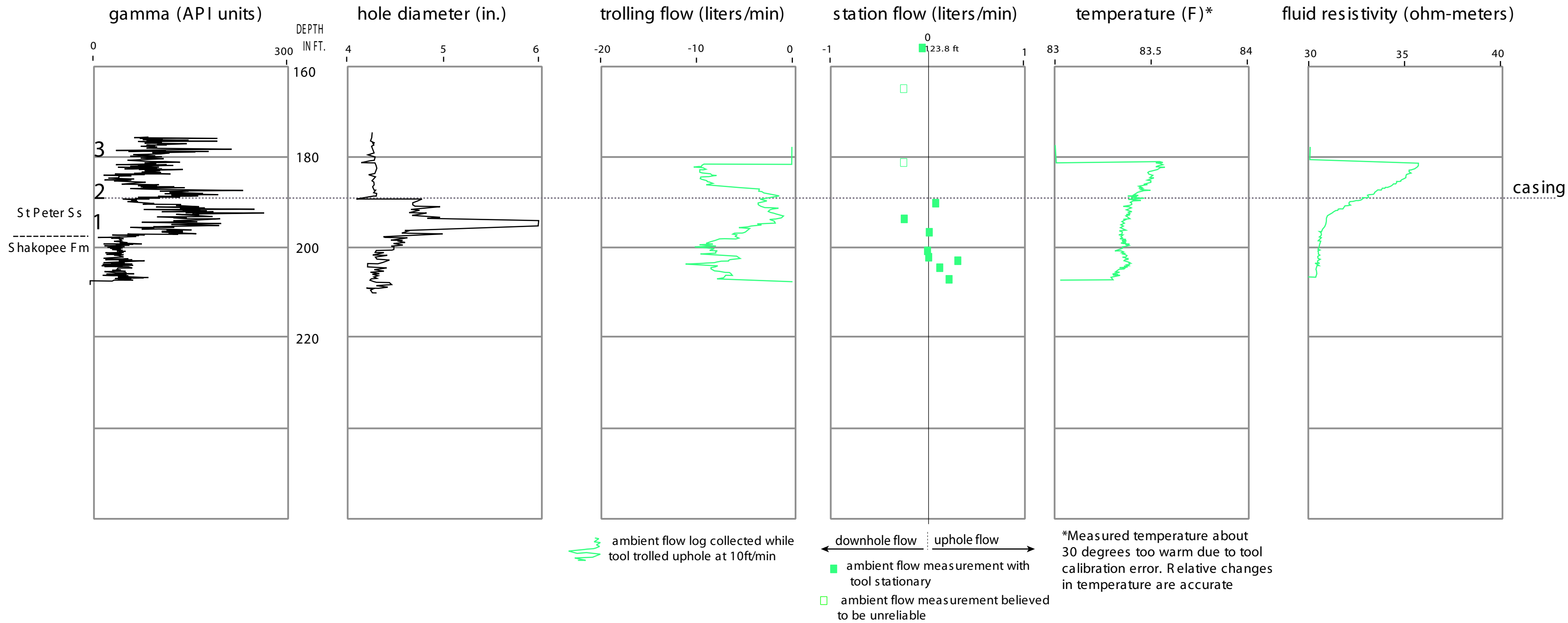
Interpretation overview: No consistent vertical flow measured. Deflection in temperature and resistivity curves, and inconsistent, weak, upflow measurement at 227 ft may indicate some cross-hole flow from fracture at that depth.

8310 27th St N (196939)



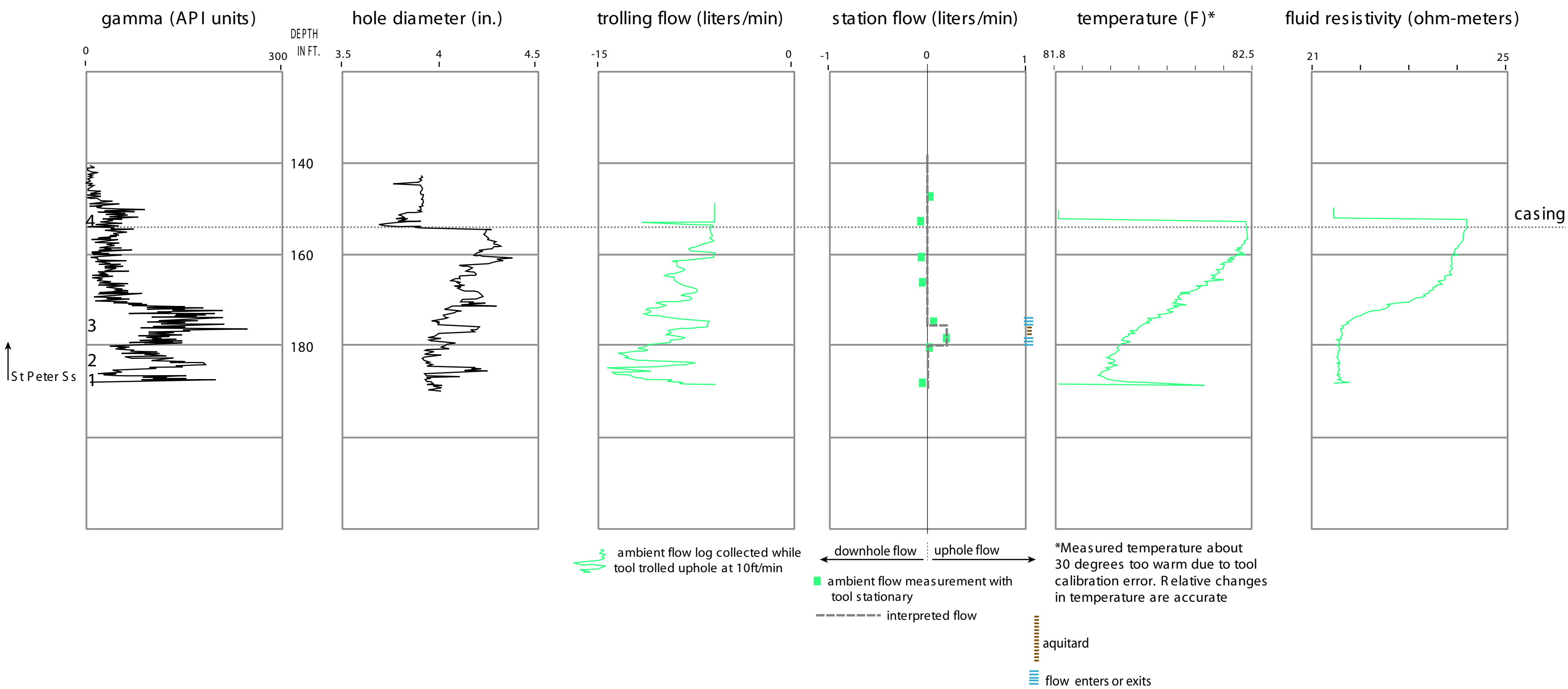
Interpretation overview: Borehole obstructions led to limited flow measurements, which indicate downhole flow of about 0.3 liters per minute that enters hole immediately below casing through fracture. Other deflections in resistivity and temperature logs at 205' and 207 ' may indicate cross-hole flow.

8655 27th St N (257171)



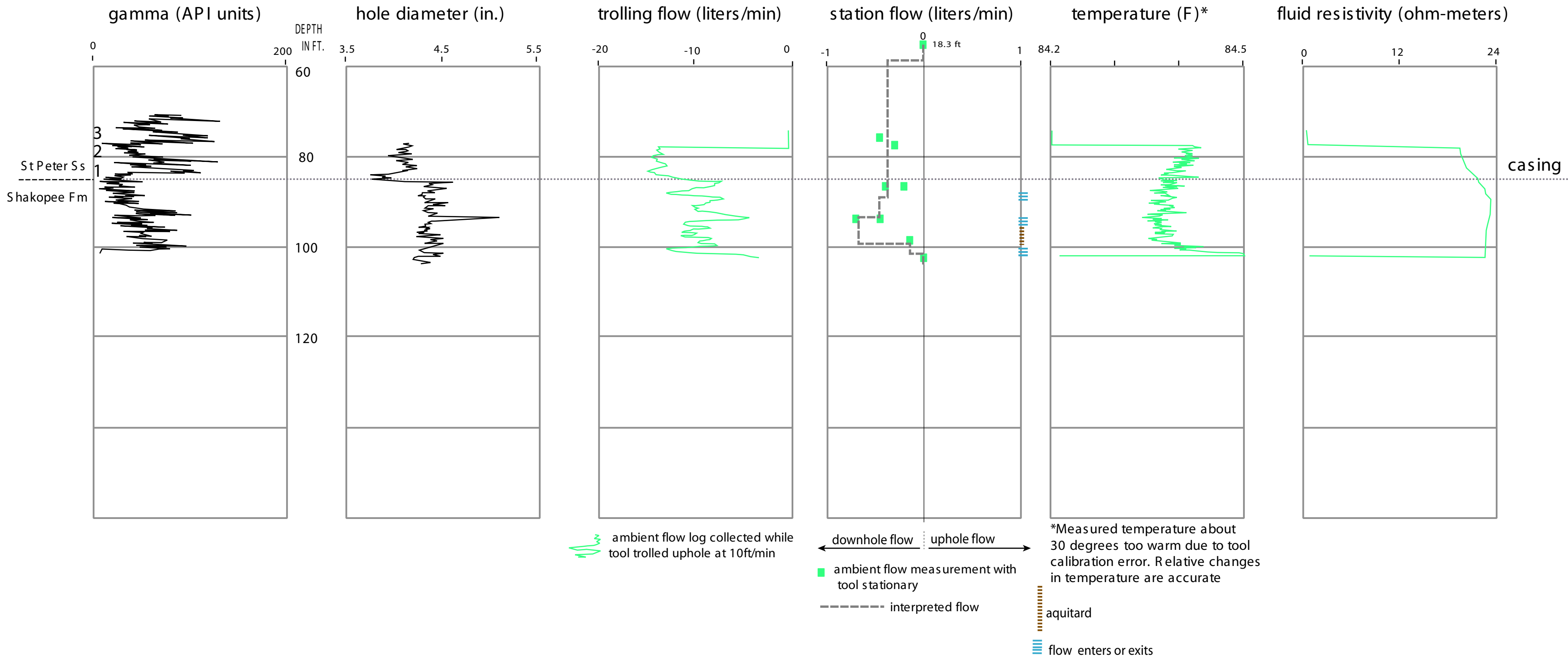
Interpretation overview: No consistent flow measured. Steady readings indicated approximately zero flow, other readings were highly variable or could not be duplicated.The latter may be the result of turbulent cross-hole flow through fractures at 194, 204, 208 ft. The trolling log curve precisely matched hole diameter, also supporting no uphole or downhole flow.

8656 27th St N (257375)



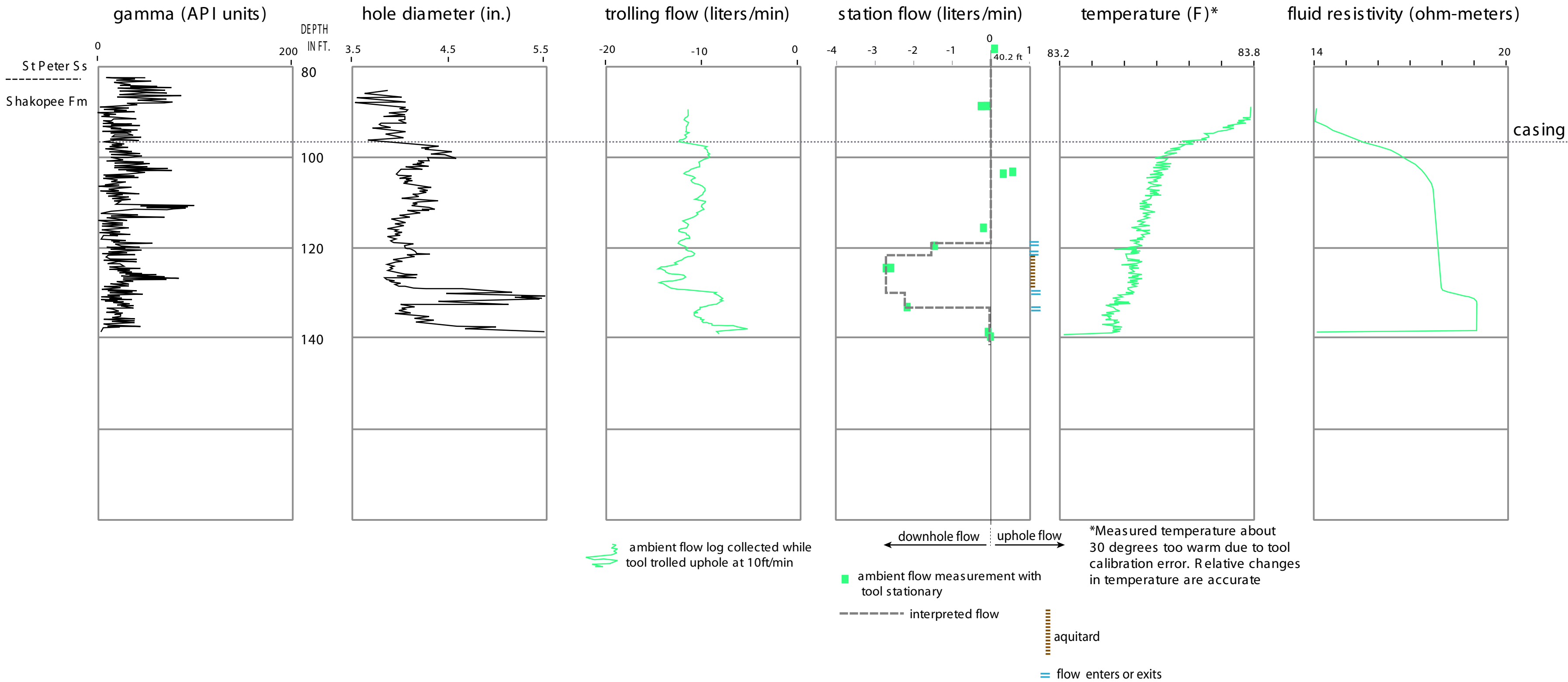
Interpretation overview: Most of open hole has no measurable vertical flow. One station measurement, and trolling log indicate there may be upflow that enters hole through fracture at 180 ft, and exits hole through fracture at 176 ft. Data collected with flow tool on 5/8/07 was adjusted such that footage moved down 5 ft to match logs collected on earlier dates.

9043 28th St N (446288)



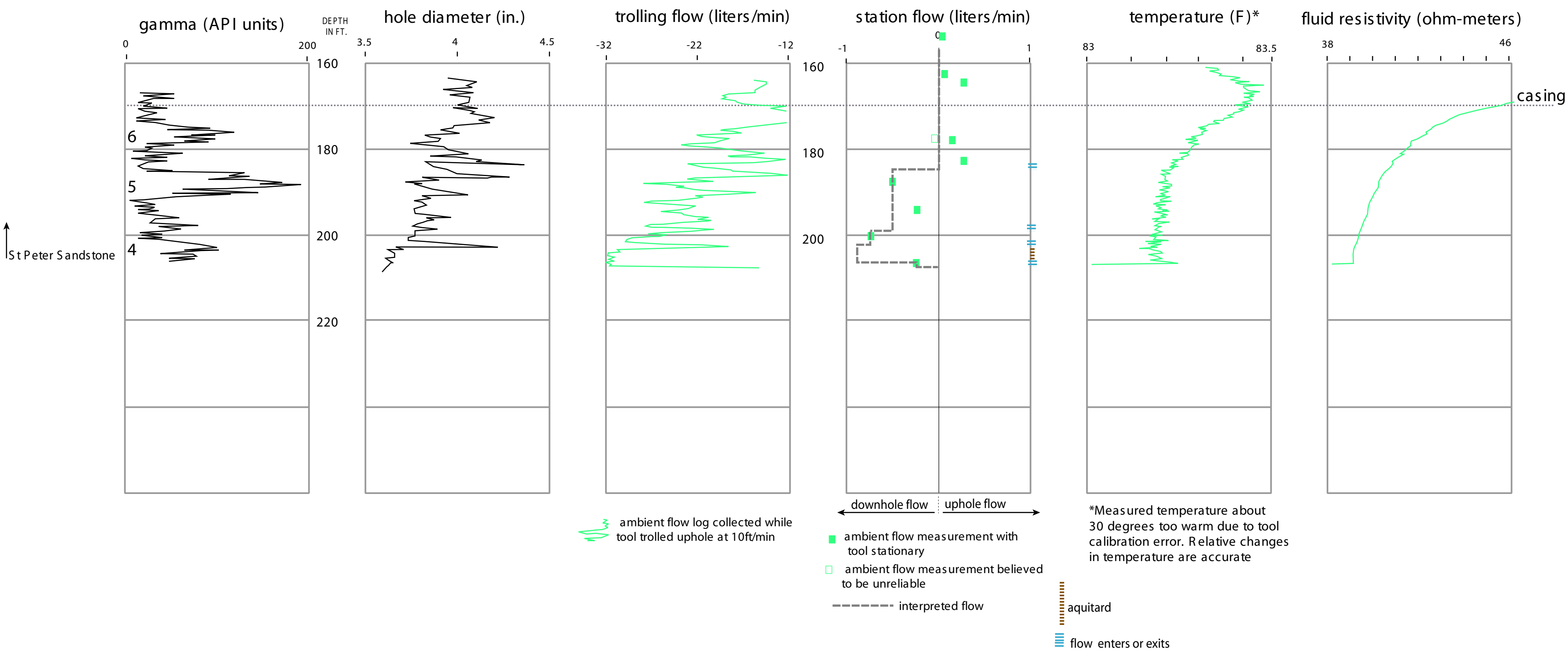
Interpretation overview: Definite downflow. Some enters from within casing, other entries in open borehole at fractures at 89 and 94 ft. Water exits at two or more fractures near bottom of hole (99 and 102 ft), where highly variable readings indicate turbulent flow.

9148 31st St N (257198)



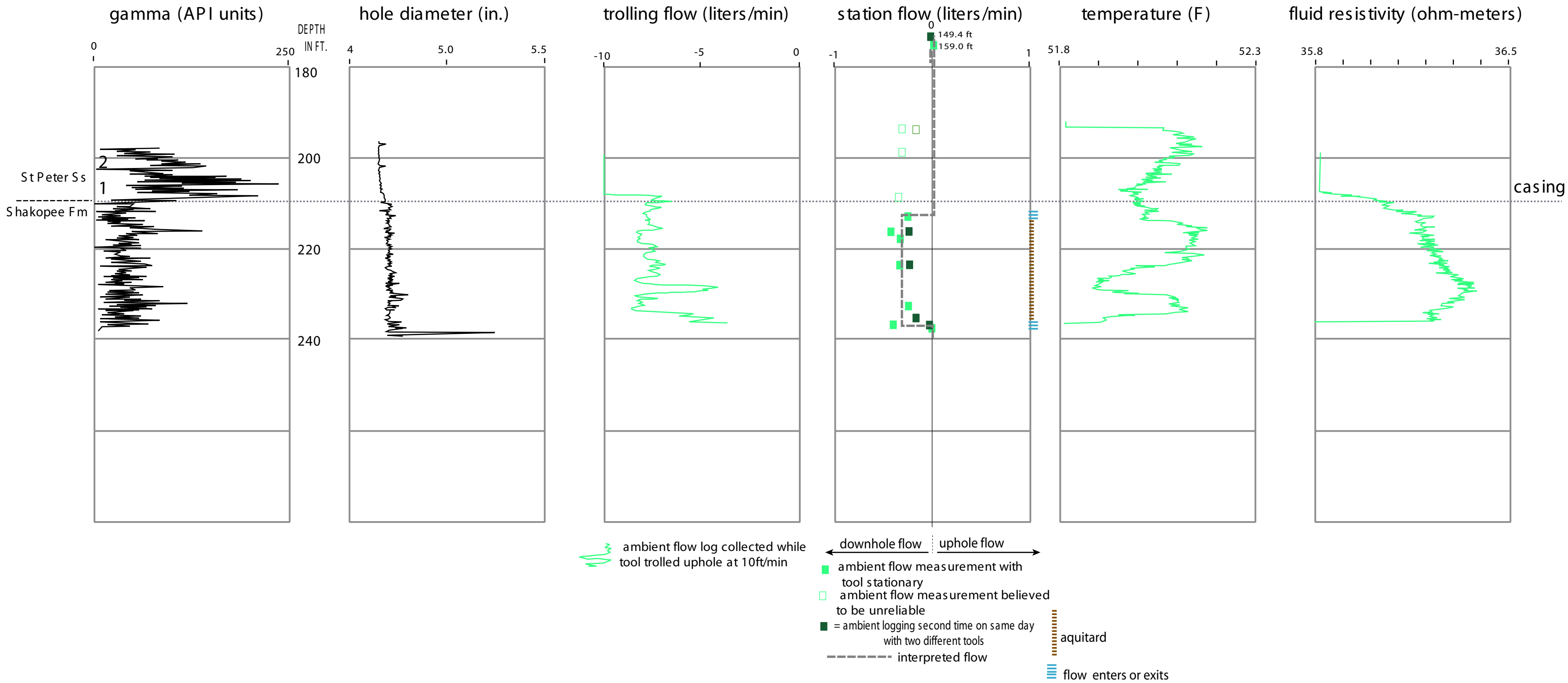
Interpretation overview: Water enters hole through fractures at 119 and 122 ft, flows downhole at a maximum measured rate of about 2.7 liters minute, and exits through fractures at 130 and 134 ft.

2528 Imperial Ave (554312)



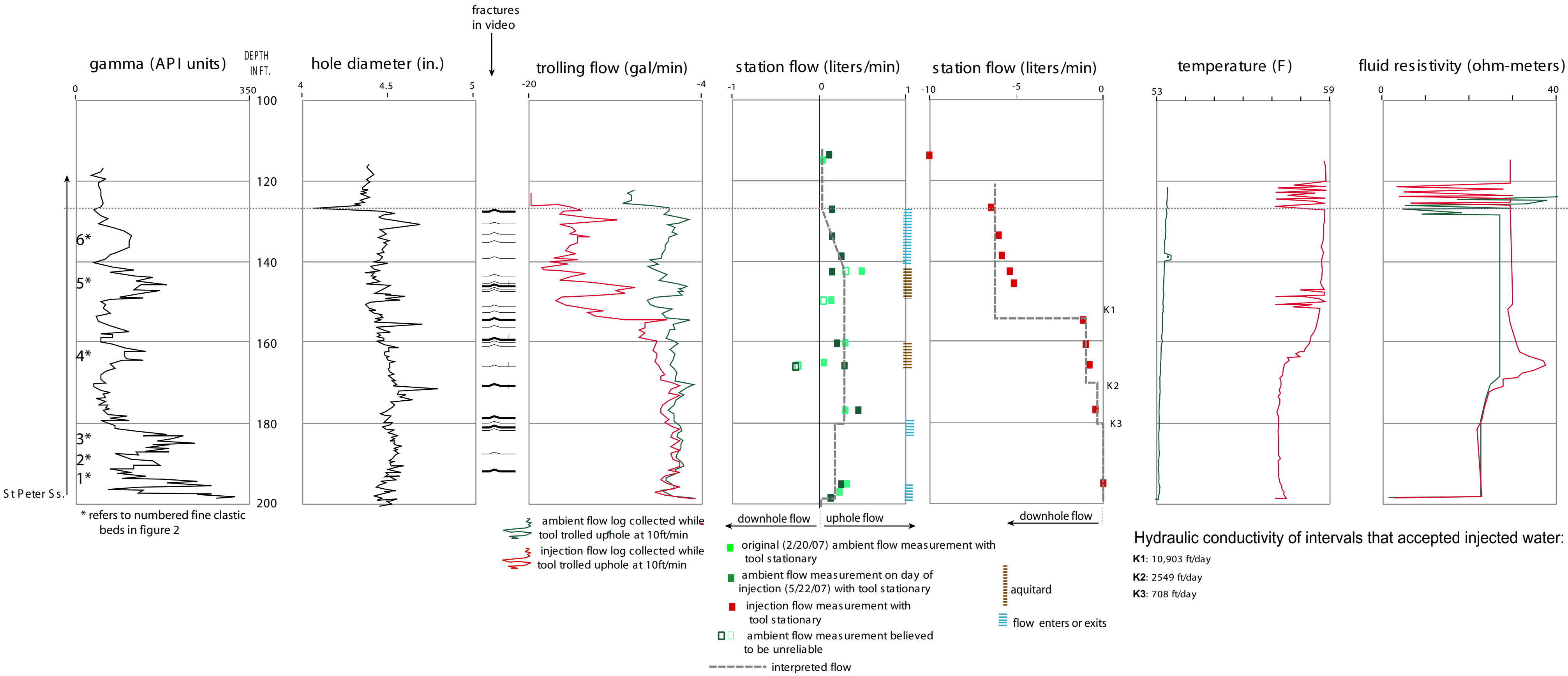
Interpretation overview: Open hole dominate by downflow at rate as high as 0.7 liters per minute. Water enters hole through fractures between 184-186 ft, and at 199 and 202 ft. Downflow exits hole at fractures between 206 and 208 ft.

2699 Imperial Ave N (678196)



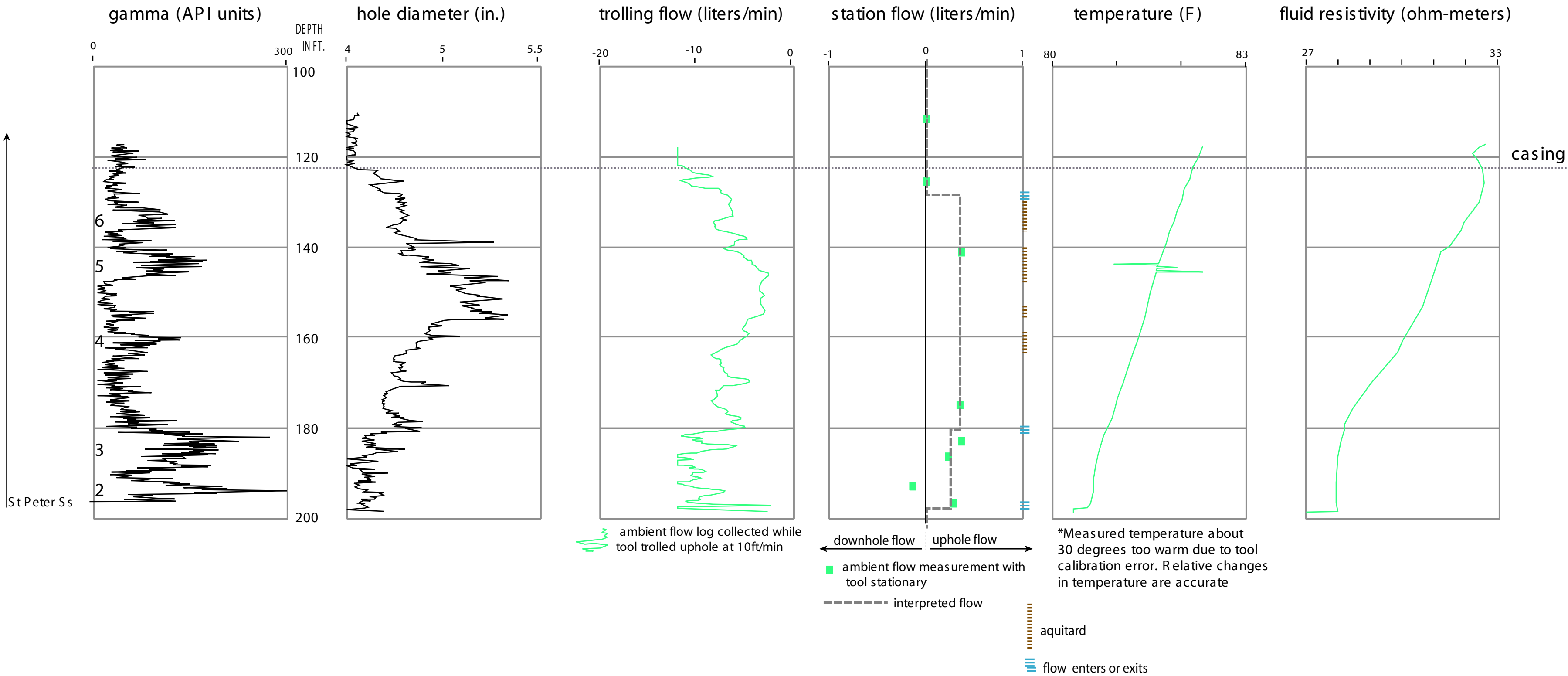
Interpretation overview: Open hole dominated by downflow at rate of about 0.35 liters/minute. Downflow originates from fracture at 212 ft, and exits hole via fracture at 237 ft. Station measurements that indicate downflow within casing were disregarded because trolling log indicates downflow originates from 212 ft rather than from within casing. If downflow does occur in casing it must originate from defect in casing and grout, and exit borehole immediately beneath casing bottom.

2760 Imperial Ave (609537)



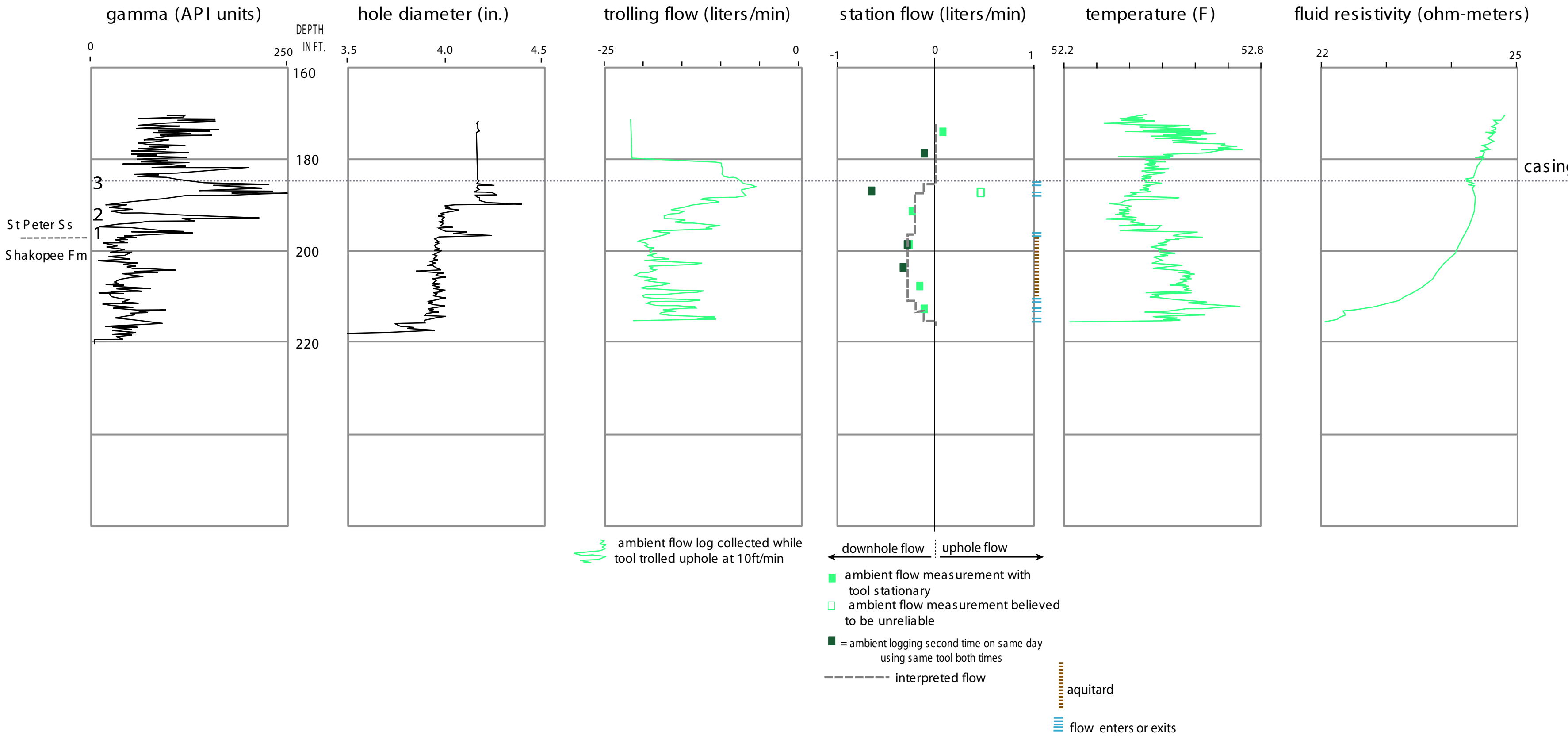
Interpretation overview: Under ambient conditions water enters borehole at one or more intervals between 180 ft and bottom of hole, and travels at a low rate (maximum 0.44 liters/min) uphole, exiting above 140 ft. Information is insufficient to clearly discriminate between fracture flow and intergranular flow where the water exits. Water injected at rate of 22.9 liters per minute exits borehole at three bedding plane fractures (K1, K2, K3) with a hydraulic conducitivty that ranged from 708 to nearly 11,000 ft/day.

2769 Imperial Ave N (614269)



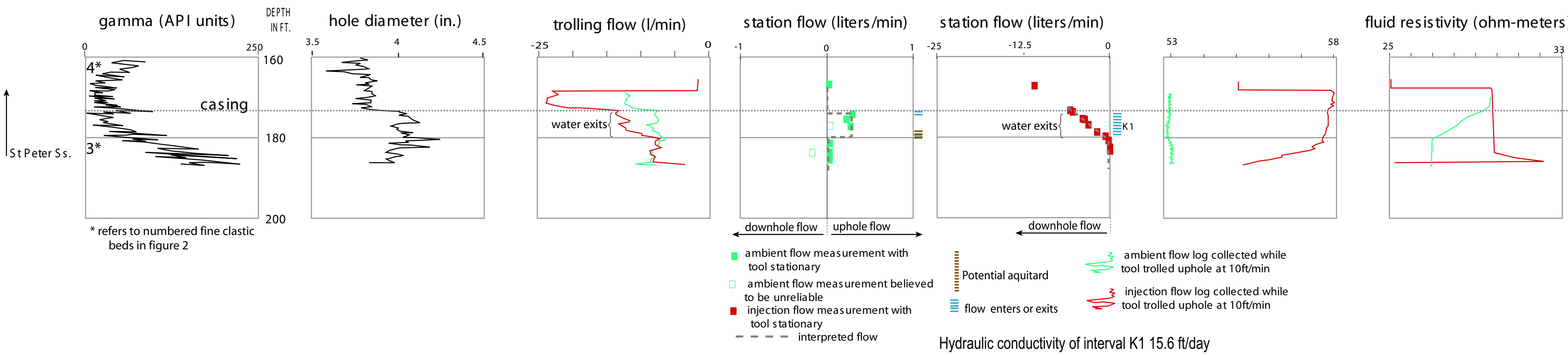
Interpretation overview: Open hole dominated by upflow at rate of about 0.4 liters minute. Water enters via fractures at 180 and 197 ft, and exits via fracture at 128 ft. Other hydraulically active fractures, based on trolling, temp and resisitivy shifts may be present at 140, 160, 162, and 192 ft., although no certain contribution or subtraction of flow could be documented.

2890 Imperial Ave N ((575148)



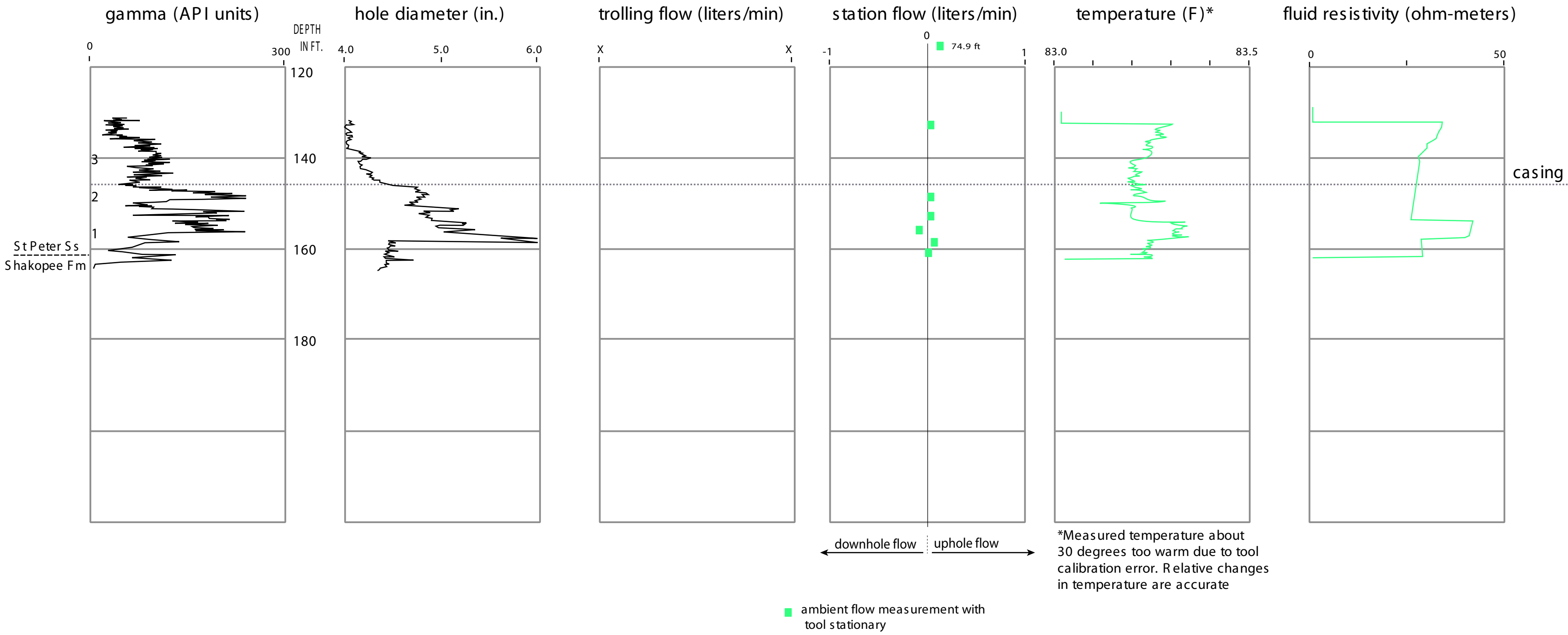
Interpretation overview: Water enters upper part of hole at three fractures (186,188,and 197 ft), flows downhole at a rate of about 0.2 liters/min, and exits hole through three fractures at 212, 214 and 216 ft. Measurements at about 187 ft and at hole bottom were greatly variable, believed to reflect turbulent flow. Trolling log across the 187 depth interval indicates downhole flow at that depth is at lower rate than lower in the hole.

2626 Innsdale Ave N (519084)



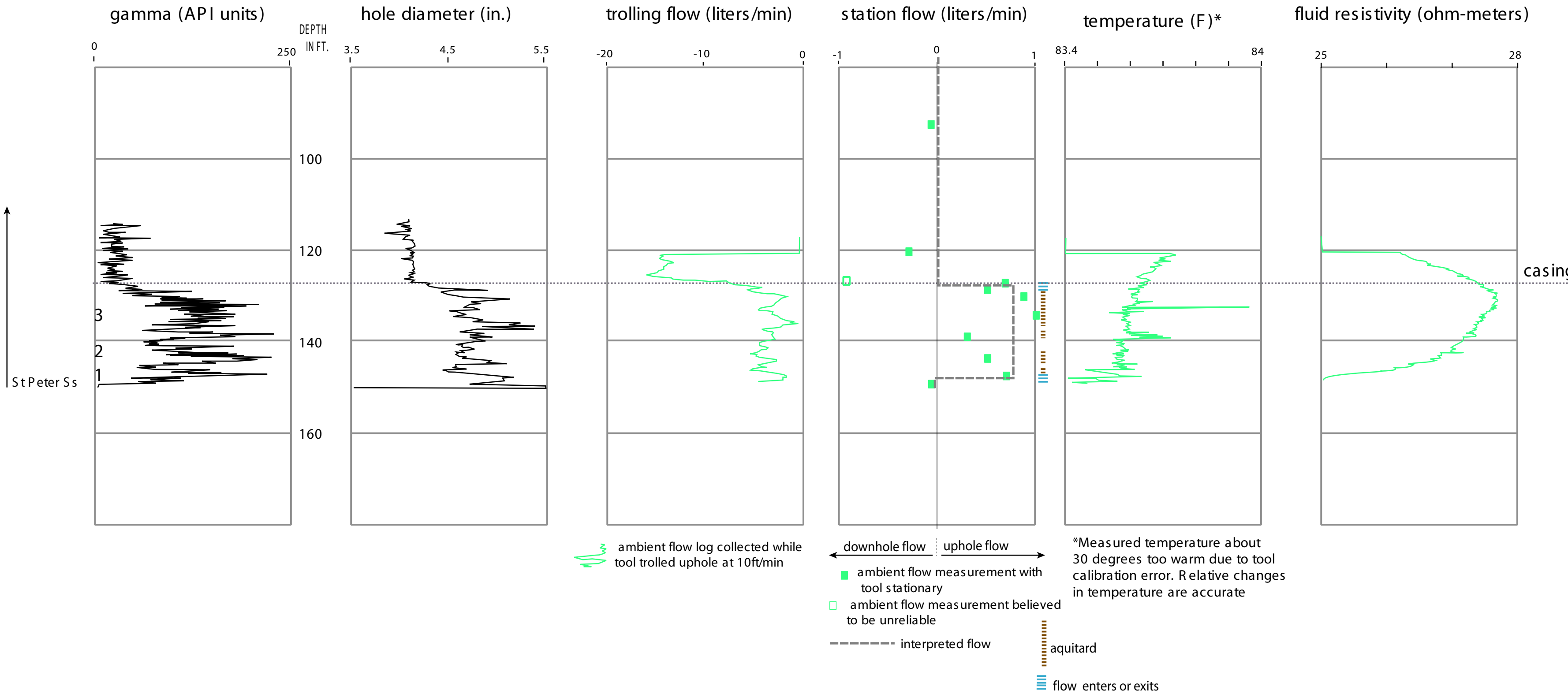
Interpretation overview: Under ambient conditions water enters borehole at about 180 ft, flows uphole at a rate of about 0.3 liters per minute, and exits about one foot or less beneath casing bottom (~174 ft). Entry and exit occurred along discrete fractures. Water injected at a rate of 22.7 liters per minute exits the borehole gradually between 173 and 180 ft, labelled K1, indicating intergranular flow. The hydraulic conductivity of this interval is 15.6 ft/day.

2915 Inwood Ave N (154443)



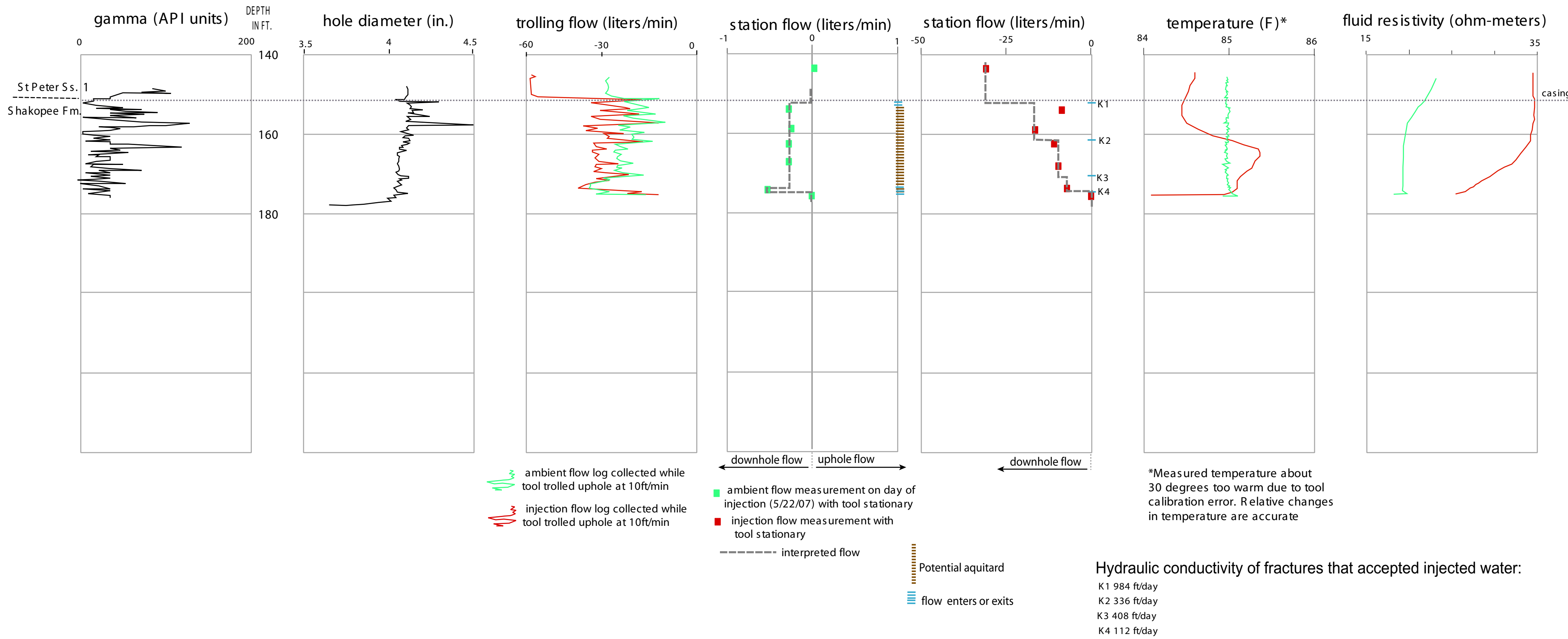
Interpretation overview: No consistent vertical flow measured. Relatively strong deflections in resistivity and temperature curves from 154 to 158 ft. may indicate cross-hole flow. Trolling log discarded because of equipment error.

3033 Inwood Ct N (622211)



Interpretation overview: Water enters borehole through fracture at approximately 149 ft, travels uphole at an average rate of about 0.8 liters minute and exits close to casing bottom through one or more fractures between 128 and 130 ft. Variablity in station measurements is believed to reflect relatively great variability in borehole diameter and turbulent flow at fractures.

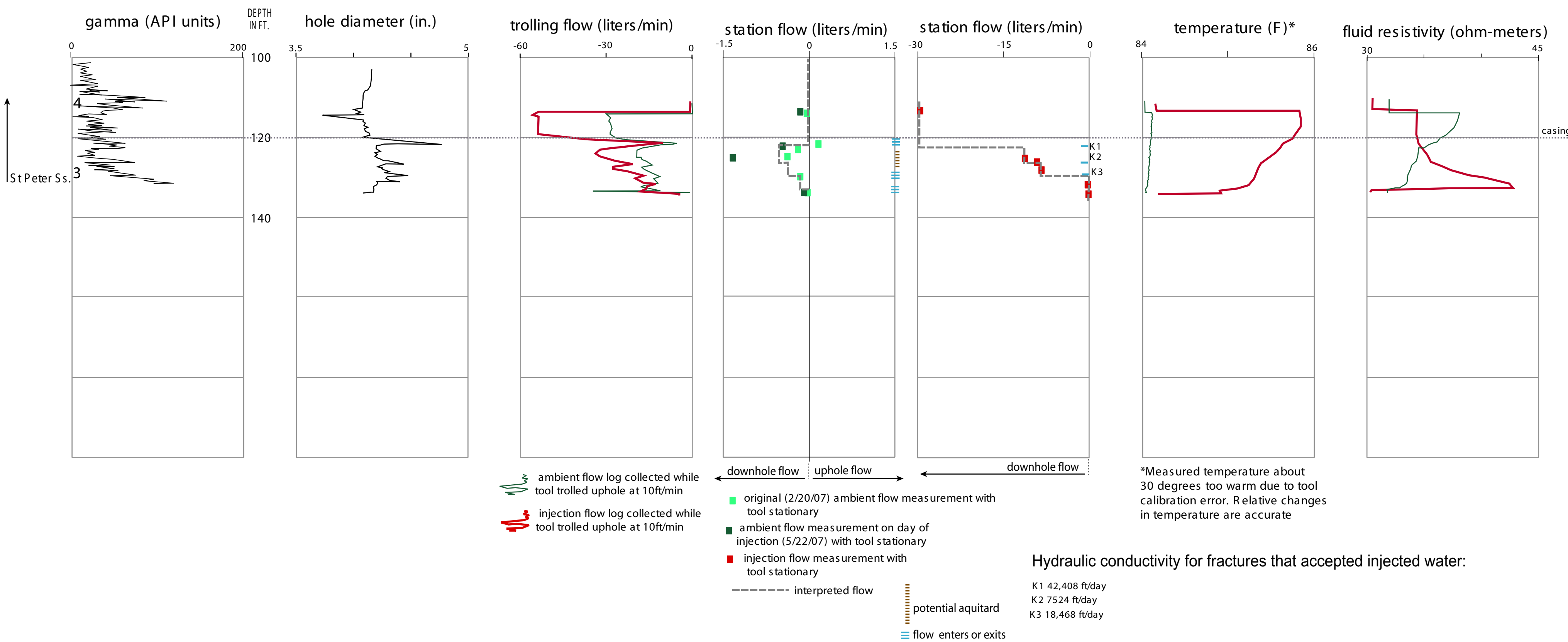
3036 Inwood Ct N (613401)



Interpretation overview: In ambient conditions water enters borehole via bedding plane fracture about one foot below bottom of casing (approx 153 ft), flows downhole (maximum rate of 0.56 liters/min measured). Additional water enters hole at approximately 174 ft, and adds to downflow. All downflow exits via bedding plane fracture at approximately 175 ft.

Injected water (22.7 liters/min) exits borehole largely through four bedding plane fractures (K1 through K4), with conductivites that range from 112 to 984 ft/day.

3082 Inwood Ct N (569744)



Hydraulic conductivity for fractures that accepted injected water:

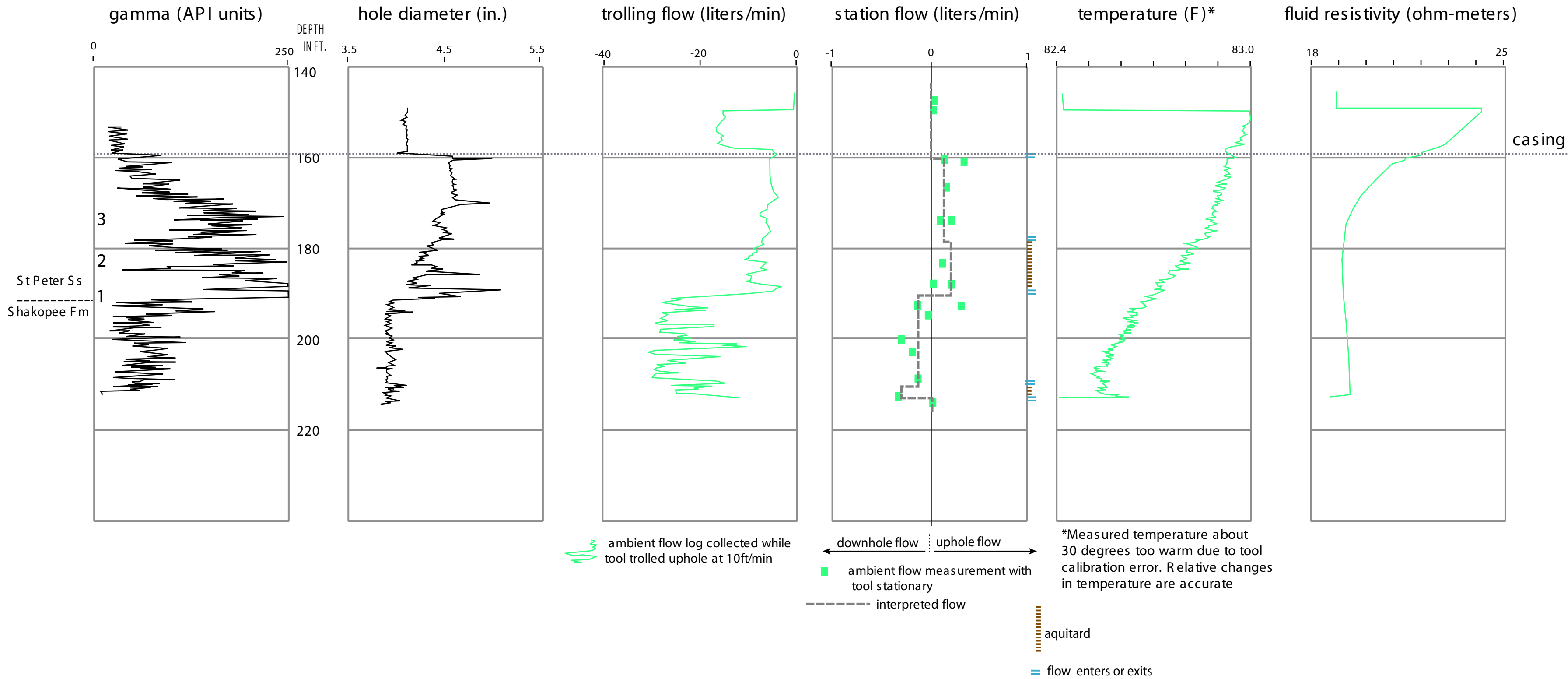
K1 42,408 ft/day
K2 7524 ft/day
K3 18,468 ft/day

Interpretation overview: Under ambient conditions water enters hole through bedding plane fractureat 123 ft., flows downhole, and exits along bedding plane fractures at 126 ft., 130 ft., and 133 ft.

Injection at 18.9 liters per minute exited at three bedding plane fractures, K1 through K3, at 122, 126, and 130 ft.

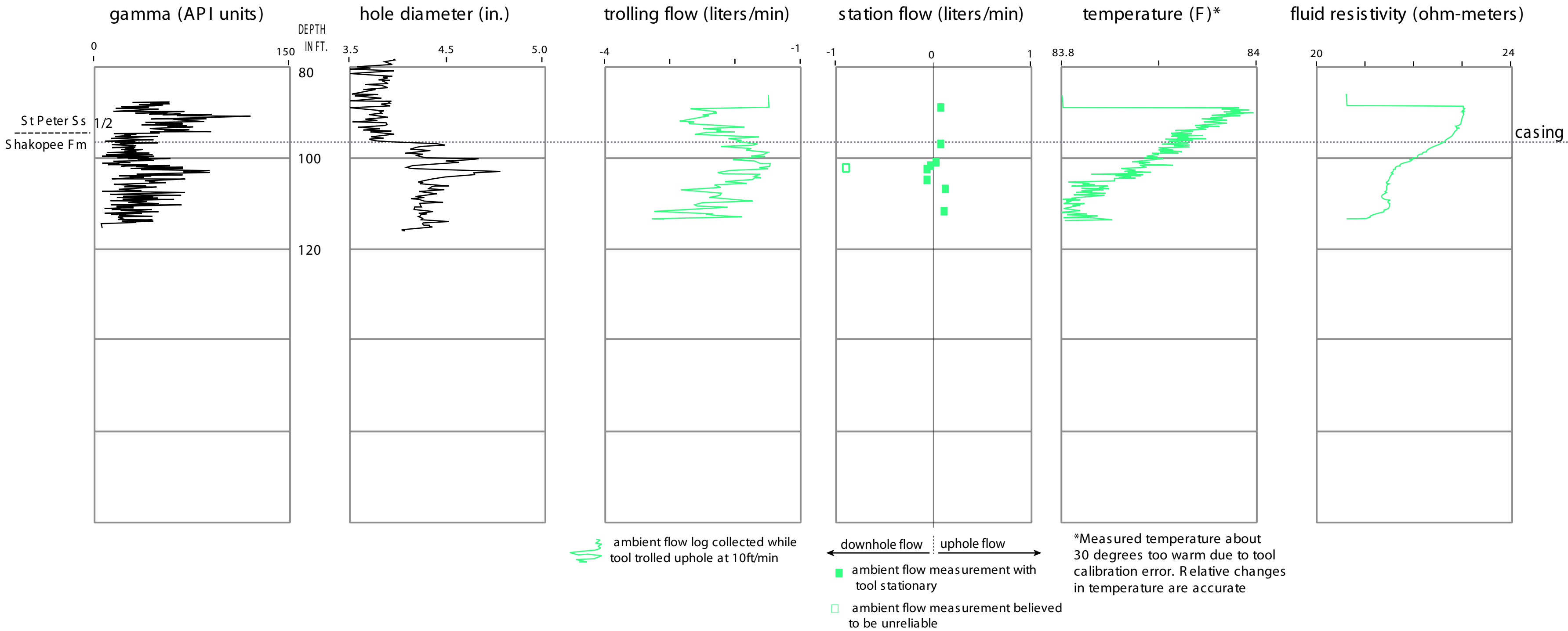
Footages for flow logs were adjusted downward about 1.5 feet to match gamma and caliper log footages collected on earlier date.

(2770 Irish Ave) (671999)



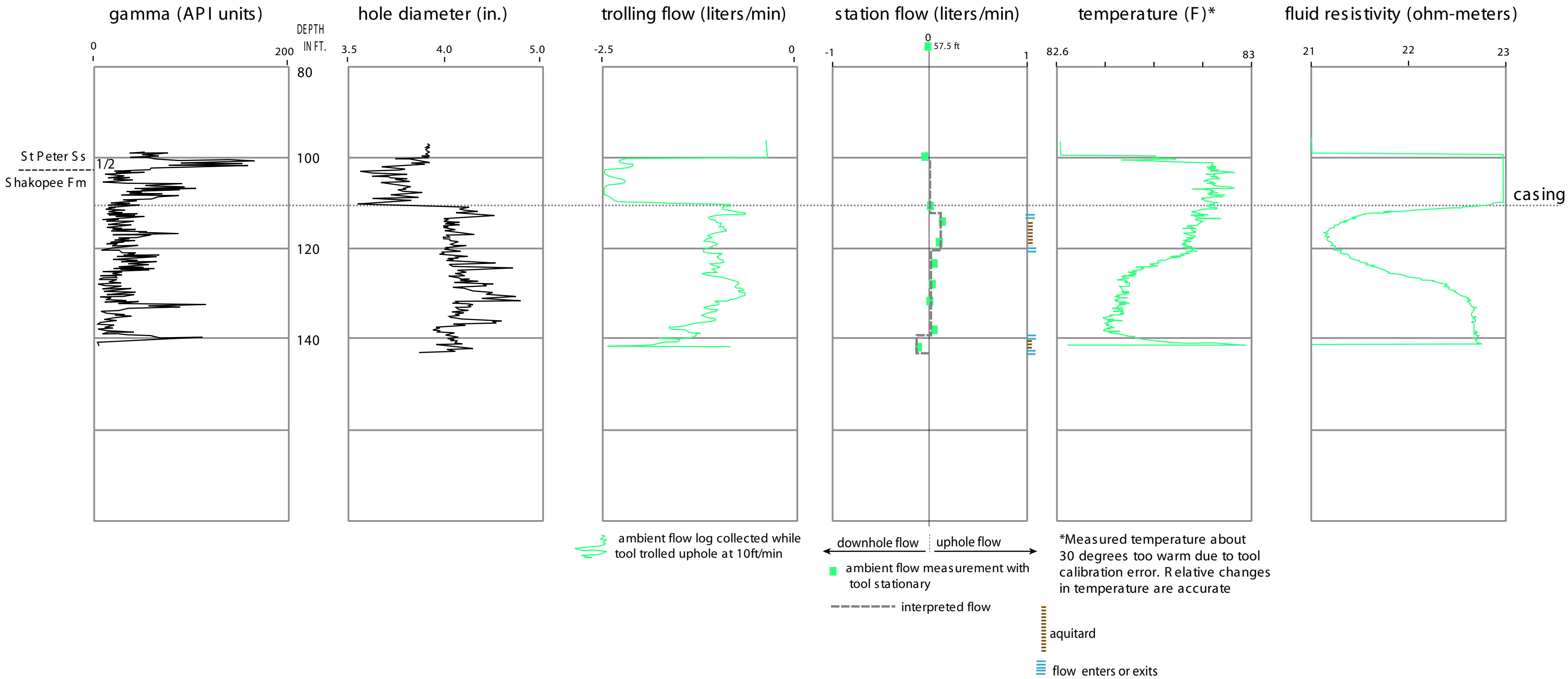
Interpretation overview: Water enters borehole through fracture at 190 ft. Some of this water flows uphole at rate of about 0.2 liters per minute, exiting through fractures at 178 and 160 ft. Remaining water flows downhole, with additional contribution to downflow through fracture at 210 ft. Downflowing water exits hole through fracture at 213 ft.

2751 Jamley (257368)



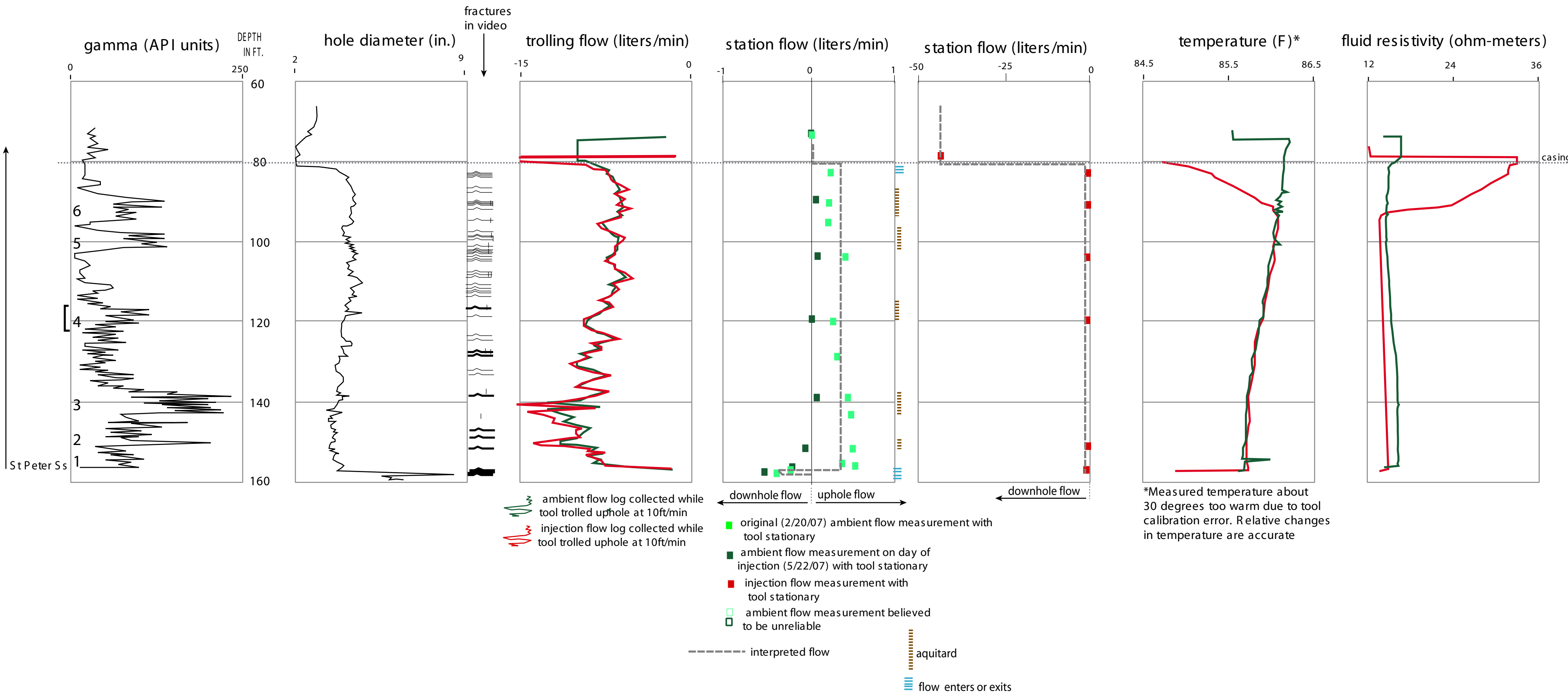
Interpretation overview: No consistent vertical flow measured with confidence. May be very weak downflow from 100 to 106 ft.

3052 Jamley Ave (208450)



Interpretation overview: Relatively weak vertical flow indicated across two intervals: Downflow enters through fracture at 140 ft and exits through fracture at 143 ft. Upflow enters at 120 ft through fracture and exits at 112 ft through fracture.

8282 Stillwater Blvd (154476)

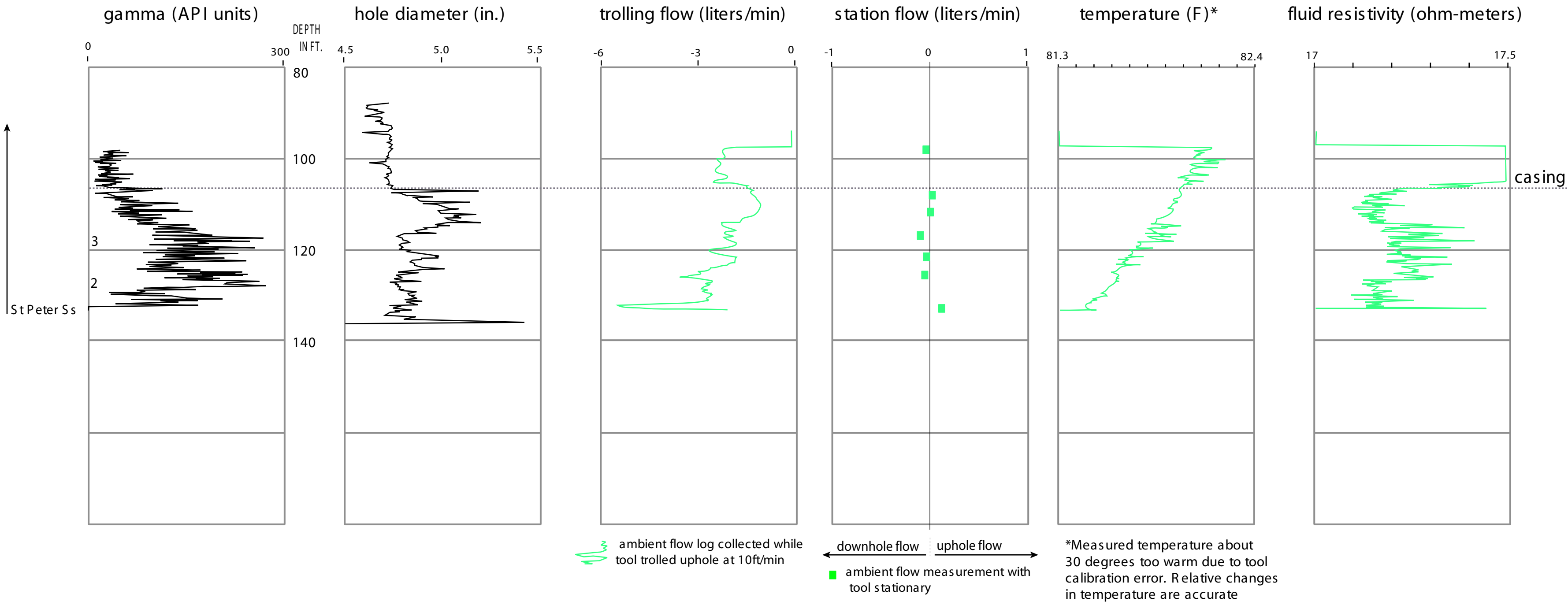


Interpretation overview: Ambient conditions during original flow logging (light green) showed water entering hole at about 157 ft, traveling uphole at about 0.35 liters/minute, and exiting at bottom of casing. An equal rate of flow downward below 157 ft appears to exit a foot or two lower via fracture(s). Downflow near bottom of holewas greatly variable, however, and may represent turbulent cross-hole flow.

Water injected at a rate of about 37.9 liters/minute exited at casing bottom.

Well is not grouted. Exiting water in both ambient and injection conditions likely traveled behind the casing.Therefore the injection test is not a measure of rock properites of the open hole interval.

8680 Stillwater (583343)



Interpretation overview: Very low flow values not significantly different from casing readings suggest no measureable upflow or downflow. Upflow measured at near hole bottom is an average of greatly variable values that ranged from negative 0.5 to positive 1.2 liters per minute, indicating turbulent flow near fracture at hole bottom.

APPENDIX D

COPIES OF ALL GAMMA, CALIPER, AND MULTI-PARAMETER GEOPHYSICAL LOGS COLLECTED IN LAKE ELMO STUDY AREA (SEE APPENDIX A FOR COMPLETE LIST)

Explanation of column headings on logs:

GAMMA: Natural gamma log, API-GR refers to American Petroleum Institute-Gamma Ray Units
RES(FL): Fluid resistivity, OHM-M refers to ohm/meters
SP: Spontaneous Potential, MV refers to millivolts
TEMP: Fluid Temperature, DEG F refers to degrees Fahrenheit
RES(16N): 16 inch Normal Resistivity, OHM-M refers to ohm/meters
RES(64N): 64 inch Normal Resistivity, OHM-M refers to ohm/meters
RES: Single Point Resistance, OHM refers to ohm
DEL TEMP: Delta Temperature, DEG F refers to degrees Fahrenheit
LATERAL: Lateral Resistivity, OHM-M refers to ohm/meters
SP COND: Specific conductance, US/CM refers to microsiemens/centimeter