



**GEOLOGICAL SURVEY OF CANADA  
OPEN FILE 7492**

**Borehole geophysical studies in a fractured sedimentary rock  
aquifer in Haldimand, Gaspé, Québec**

**H. Crow, M. Raynauld, R. Lefebvre, E. Gloaguen,  
K. Brewer, T. Cartwright**

**2014**



Natural Resources  
Canada

Ressources naturelles  
Canada

**Canada**



**GEOLOGICAL SURVEY OF CANADA  
OPEN FILE 7492**

**Borehole geophysical studies in a fractured sedimentary rock  
aquifer in Haldimand, Gaspé, Québec**

**H. Crow<sup>1</sup>, M. Raynauld<sup>2</sup>, R. Lefebvre<sup>2</sup>, E. Gloaguen<sup>2</sup>, K. Brewer<sup>1</sup>,  
T. Cartwright<sup>1</sup>**

<sup>1</sup> Geological Survey of Canada (Ottawa), 601 Booth Street, Ottawa, ON K1A 0E8

<sup>2</sup> Institut national de la recherche scientifique, 490 rue de la Couronne, Québec, QC G1K 9A9

**2014**

©Her Majesty the Queen in Right of Canada 2014

doi:10.4095/293363

This publication is available for free download through GEOSCAN (<http://geoscan.ess.nrcan.gc.ca/>).

**Recommended citation**

Crow, H., Raynauld, M., Lefebvre, R., Gloaguen, E., Brewer, K., Cartwright, T. 2014. Borehole geophysical studies in a fractured sedimentary rock aquifer in Haldimand, Gaspé, Québec; Geological Survey of Canada, Open File 7492. doi:10.4095/293363

# Table of Contents

1	INTRODUCTION.....	1
1.1	Regional and Geological Setting .....	2
2	FIELDWORK.....	3
3	PROCESSING .....	7
4	INTERPRETATION AND ANALYSIS.....	8
4.1	Lithological Interpretation.....	8
4.2	Structural Interpretation .....	10
4.3	Fluid Analyses .....	12
4.3.1	<i>Temperature</i> .....	14
4.3.2	<i>Fluid Conductivity</i> .....	14
4.3.3	<i>Flow Meter</i> .....	15
4.3.4	<i>Video Logs</i> .....	15
5	SUMMARY .....	17
6	DISCUSSION.....	18
6.1	Depth or Elevation? What is the Main Influence on Lithology and Groundwater Flow? .....	18
6.2	Faulting as a Structural Control? .....	18
6.3	Recommendations for Future Similar Projects.....	18
	ACKNOWLEDGEMENTS.....	21
	REFERENCES .....	21
	APPENDIX I - Interpreted Geophysical Log Suites	
	APPENDIX II - Geophysical Log Background	
	APPENDIX III - Digital Data Files	

## 1 INTRODUCTION

To investigate a potential link between an 800 m-deep petroleum reservoir and a shallow fractured rock aquifer system, the Institut national de la recherche scientifique (INRS) is conducting a groundwater study in the Haldimand Sector of Gaspé, Québec. In 2011 and 2012, 15 new observation wells were drilled and groundwater was sampled in these, and three pre-existing, wells. Surface water was also sampled across the site. To support the study and evaluate the downhole tools best suited for this type of investigation, the Geological Survey of Canada (GSC) collected geophysical logs in 10 open rock and 3 PVC-cased wells during the fall of 2012 (Table 1). Logs were acquired to better understand the lithological variations in the near-surface sedimentary rock, *in situ* variation in fluid temperature & conductivity, flow rates and direction of flow along the wellbore, and the structural orientations of fractures intersected by the boreholes.

Table 1 – Well locations and elevations.

Well	UTMs (NAD 83, Zone 20)		Open/Cased Method/diam.	Depth Drilled (m)	Surface Elevation (MASL)
	Easting	Northing			
POH-11-02	395 921	5 407 159	open, hammer, 152 mm	42.1	94.11
POH-11-03	394 098	5 408 228	open, cored, 76 mm	51.0	60.25
POH-11-04	395 965	5 407 683	PVC-cased, hammer, 152 mm	41.9	76.41
POH-11-05	393 925	5 407 957	open, hammer, 152 mm	42.7	91.27
POH-11-06	395 904	5 406 475	open, hammer, 152 mm	36.0*	47.53
POH-11-09	395 574	5 407 156	open, hammer, 152 mm	46.3**	83.92
POH-11-10	395 575	5 407 620	open, cored, 76 mm	51.5	75.87
POH-11-12	394 629	5 406 859	open, hammer, 152 mm	40.2	119.44
POH-11-14	394 727	5 407 765	open, hammer, 152 mm	40.0	82.03
POH-11-15	393 947	5 407 643	PVC-cased, hammer, 152 mm	19.8	84.37
PH-01	395 520	5 406 827	open, hammer, 152 mm	44.5	79.88
PH-02	394 660	5 407 212	open, hammer, 152 mm	27.0	100.61
PH-04	393 956	5 407 759	PVC-cased, hammer, 152 mm	40.0	84.80

\*Blocked at 23.9 m at time of logging

\*\*Blocked at 25.0 m at time of logging

Analyses of these geophysical, hydrogeological, and hydrogeochemical datasets are the basis for conceptual and numerical models of the groundwater system, currently being developed at the INRS. Ultimately, an improved understanding of groundwater flow in the area will allow for an assessment of potential impact to groundwater quality from local petroleum industry activities.

This report describes the geophysical logging carried out on site by the GSC, presents the findings of the downhole dataset analyses, and provides the interpreted log figures and digital log data in Appendices I and II. In tandem with these analyses, groundwater sample analyses are being conducted, and current results have been described in Raynauld et al. (2013b).

## 1.1 Regional and Geological Setting

The field site is located within the municipality of Gaspé, Québec, in the Haldimand sector 3 to 7 km from downtown Gaspé. The sedimentary rock surface is folded and elevation varies from sea level to 200 m in the center of the Haldimand peninsula, bounded by the St. Jean and York Rivers (Figure 1). Provincial Highway 132 runs around the inhabited edge of the peninsula, while its forested interior is only accessible through trails on private land. The principal source of groundwater in the region is the near-surface fractured sedimentary rock aquifer, and local residential wells are drilled to an average depth of 30.5 m (Raynauld et al., 2013a). The primary users of groundwater in the study area are local residents.

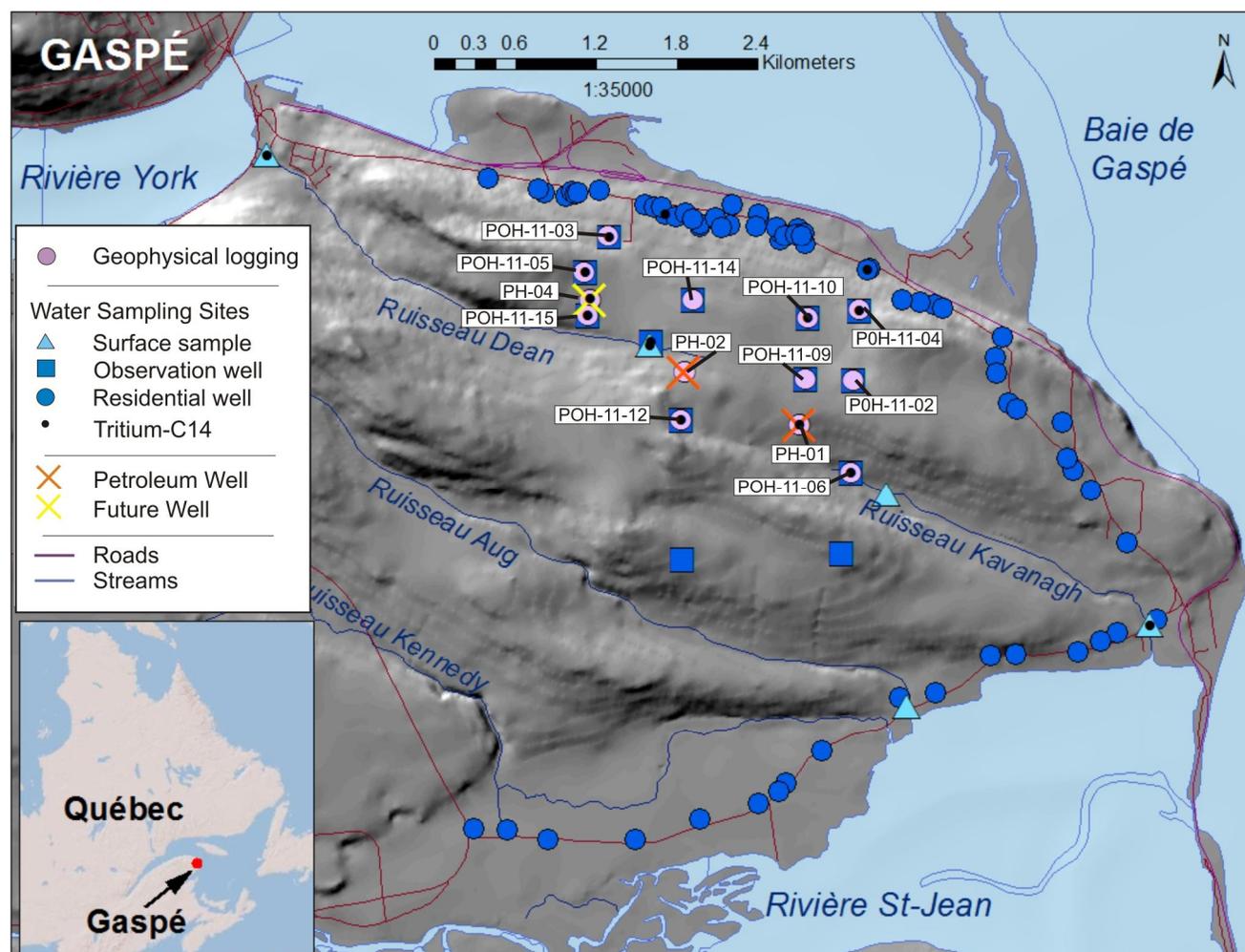


Figure 1 – Locations of the boreholes logged during the GSC field campaign, along with sites where water samples were collected in 2012. Modified from Raynauld et al., 2012.

The near surface sedimentary rock in the area is composed of Devonian-age fluvial sandstone and mudstone sequences of the Battery Point Formation (Desbiens, 1990), which extend hundreds of metres below surface. Deep hydrocarbon reservoirs are found within the underlying York River Formation at depths ranging between 630 and 1200 m. For more information on the reservoir geology, see Petrolia (2013a and 2013b).

The region is known for its hydrocarbon potential, and natural hydrocarbon seeps are present at several locations near Haldimand. Historic petroleum exploration activity has led to abandoned

shallow wells in the area. Two recent exploration wells have been drilled in the region (Petrolia Haldimand No. 1 and Petrolia Haldimand No. 2), which reach the top of the reservoir in the York River formation at depths of 930 m and 722 m, respectively. Haldimand No. 1 has been producing at a moderate non-commercial rate. A third exploration well, Petrolia Haldimand No. 4, is waiting for full authorization to begin drilling. Each deep well is located next to a 6" water well (PH-series) that was used to provide groundwater for the drilling. Well PH-04 was drilled near Petrolia Haldimand No. 4 in October 2012.

A hydrogeological characterization was carried out in 2011 and 2012 by TechnoRem (2013), a hydrogeological consulting firm from Laval. Twelve 6" (152 mm) boreholes were hammer-drilled in 2011 for the groundwater study. In the fall of 2012, two additional cored 3" (76 mm) boreholes were drilled. Of these 17 shallow groundwater monitoring boreholes on site, the 13 boreholes listed in Table 1 were accessible for geophysical logging.

## 2 FIELDWORK

Field work was carried out by a two-person GSC crew between October 30 – November 19, 2012. Table 2 contains a summary of the logs collected in each borehole, and Table 3 describes each tool's resolution, basic collection parameters, and the practical interpretation of each log. A more detailed description of the tools can be found in Appendix II.

Geophysical logs provide a means of identifying and characterizing lithological units based on variations in their chemical and physical properties. "Lithological logs" (spectral gamma, inductive and guard resistivity, magnetic susceptibility) augment geological interpretation when cores cannot be retrieved, and allow for correlation of marker horizons or geological units between wells. The group of logs known as "hydrogeophysical" (fluid temperature/conductivity, flow meter, caliper) detects vertical fluid movement in the borehole caused by flowing fractures intersected by the wellbore. Temperature logs can also be used to infer fluid movement behind PVC casing. Finally, the acoustic televiewer (ATV) collects high-resolution (mm-scale) amplitude and time images of the inside of the borehole wall. This allows for analysis of wall roughness, orientation of structural features cross-cutting the borehole, and estimation of the fracture aperture at the borehole wall. The televiewer log can be considered structural, hydrogeophysical, and to a lesser extent, lithological, in groundwater studies. To accompany the televiewer images, a video camera was used to record moving images of gas bubbles or particle movement in the groundwater, and assess overall well condition.

Prior to leaving for the field, laboratory calibrations were performed with the temperature tool, flow meter, and orientation systems of the ATV tool. Additional calibrations were performed after returning from the field with the temperature and fluid conductivity tools.

The water level was measured in the borehole upon arrival at each well site. The fluid temperature and conductivity tools were the first instruments lowered into the borehole to collect the log in undisturbed fluid. A period of 10-20 minutes was allowed for the tools to thermally equilibrate in the top of the water column before the logging began. Video logging was performed next to avoid degrading fluid clarity with centralized tools which rub the borehole wall. Natural gamma, inductive conductivity, magnetic susceptibility, and resistivity were then collected in any order, followed by the televiewer. Once the televiewer, video, and fluid logs were reviewed together, intervals for the heat pulse flow meter tests were selected to bracket visible deviations in the fluid logs and/or open fractures seen in the ATV images.

In cased wells, tools which must come into contact with the borehole wall (resistivity), image the rock walls (televiewer, video camera), or interact with the fluid in the open well (fluid conductivity, flow meter) could not be used.

Table 2. Geophysical logs collected in Haldimand during the Oct/Nov 2012 field trip.

Borehole	Open rock / PVC-cased	Geophysical Log								
		Structural	Hydrogeophysical			Lithological				Video Log
		ATV (& caliper)	Flow Meter	Fluid Cond	Fluid Temp	Mag. Susc.	Nat Gam.	Ind.. Res.	Guard Res.	
PH-01	Open	✓		✓	✓	✓	✓	✓	✓	✓
PH-02	Open	✓	✓	✓	✓	✓	✓	✓	✓	✓
PH-04	Cased				✓	✓	✓	✓		✓
POH-11-02	Open	✓	✓	✓	✓	✓	✓	✓	✓	✓
POH-11-03	Open	✓	✓	✓	✓	✓	✓	✓	✓	✓
POH-11-04	Cased				✓	✓	✓	✓		
POH-11-05	Open	✓	✓		✓	✓	✓	✓	✓	✓
POH-11-06	Open	✓		✓	✓	✓	✓	✓	✓	✓
POH-11-09	Open	✓	✓	✓	✓	✓	✓	✓	✓	✓
POH-11-10	Open	✓	✓	✓	✓	✓	✓	✓	✓	✓
POH-11-12	Open	✓	✓	✓	✓	✓	✓	✓	✓	✓
POH-11-14	Open	✓	✓	✓	✓	✓	✓	✓	✓	✓
POH-11-15	Cased				✓	✓	✓	✓		

Table 3. Summary of the downhole geophysical log suite.

<b>Downhole Geophysical Log</b> <i>[Manufacturer]</i>	<b>Logging Unit</b>	<b>Radius of Investigation</b> <i>[Vertical resolution]</i>	<b>Logging Speed</b>	<b>Logging Interval</b>	<b>Practical interpretations in open rock</b>
<b>Acoustic Televiewer</b> <i>[Advanced Logic Technology/ Mount Sopris]</i>	Dual images: Traveltime (millisec) Amplitude (unitless)	Open face of borehole wall  Minimum azimuthal resolution: 1.25 pixel/deg  <i>[Minimum scan width: 0.001 m]</i>	0.5 m/min	0.001 m	In open rock: structural orientation (strike direction & dip), fracture aperture at borehole wall
<b>Acoustic Caliper</b> Interpreted from ATV traveltime data	mm	Open face of borehole wall  [Caliper resolution: 0.0001 m]	0.5 m/min	0.001 m	Wall roughness, fracture aperture at borehole wall
<b>Heat Pulse Flow meter</b> <i>[Mount Sopris]</i>	US Gal/min	Within borehole  0.03 USGal/min	Stationary readings	User selected; based on ATV and fluid temp. results	Direction and volume of vertical flow
<b>Fluid Conductivity</b> <i>[GSC]</i>	Frequency, converted to conductivity $\mu\text{S/cm}$	Influenced by surrounding materials  <i>[logging interval]</i>	1 m/min	0.01 m	Anomalies due to groundwater flow; changes in groundwater conductivity, lithology
<b>Fluid Temperature</b> <i>[GSC]</i>	Frequency, converted to degrees Celcius ( $^{\circ}\text{C}$ )	Influenced by surrounding materials  <i>[logging interval]</i>	1 m/min	0.01 m	Anomalies due to groundwater flow; lithology (as related to thermal conductivity)
<b>Magnetic Susceptibility</b> <i>[Geonics/Mount Sopris]</i>	parts per thousand SI (ppt SI)	0.3 m  <i>[submetre]</i>	3 m/min	0.02 m	Magnetite (heavy mineral) concentration, lithological boundaries
<b>Spectral Gamma</b> <i>[Mount Sopris]</i>	Counts per second (cps)	0.3 - 0.6 m  <i>[centimetres, function of logging speed]</i>	1 m/min	0.01 m	Relative grain-size, lithological boundaries

<b>Downhole Geophysical Log</b> <i>[Manufacturer]</i>	<b>Logging Unit</b>	<b>Radius of Investigation</b> <i>[Vertical resolution]</i>	<b>Logging Speed</b>	<b>Logging Interval</b>	<b>Practical interpretations in open rock</b>
<b>Inductive Conductivity/ Resistivity</b> <i>[Geonics/Mount Sopris]</i>	milliSiemens /metre (mS/m) or Ohm-metres (Ohm-m)	0.3 m <i>[submetre]</i>	3 m/min	0.02 m	Formation conductivity (grain and/or porewater conductivity), lithological boundaries
<b>Guard Resistivity</b> <i>[Mount Sopris]</i>	Ohm-metres (Ohm-m)	0.15 – 0.20 m <i>[2 cm]</i>	3 m/min	0.02 m	Relative formation resistivity, lithological boundaries
<b>Video Camera (Forward Looking)</b> GeoVISION	cm	Open face of borehole wall  [encoder resolution: 0.01 m]	Lowered by hand ~2-3 m/min	cm-scale	Borehole condition, movement of gas bubbles or particles in fluid column, inflow of fluid into well

Geophysical data were acquired using a Mount Sopris logging system with a Matrix console and interchangeable downhole probes, with the exception of the fluid tools and the downhole video camera. A laptop computer recorded the data using the Matrix logging software. The fluid temperature/conductivity logs were collected with in-house tools coupled with an IFG winch and GSC logging software. On site calibrations were carried out with the inductive resistivity and magnetic susceptibility tools before the logging runs. The downhole black and white GeoVISION camera system was lowered down the borehole by hand to control speed, and to stop and record features of interest. Depths are recorded using an encoder wheel, and the digital images are recorded to computer as .MPEG files. For all logging tools, corrections for sensor offset and casing stick up were made prior to logging, and logs were recorded relative to ground surface.

The acoustic televiewer was centralized in the borehole using a pair of aluminum, four-arm, bowspring centralizers. As decentralization negatively affects the quality of the image, care was taken to ensure the tool was well centered in the borehole before the log was recorded. Due to the 152 mm borehole diameter, the maximum resolution was used for the logging (288 pts per revolution, or 1.25 pixels/deg, with 0.001 m logging intervals). The logs were collected from the bottom of the hole upwards to keep constant tension on the wireline at low logging speeds.

During heat pulse flow meter testing, ambient flows (i.e. natural upward/downward fluid gradients) were observed in all of the wells except PH-02. Measured flows ranged between 0.04 and 3.67 l/min (0.01 and 0.97 US Gal/min), although the tool is calibrated for flows between 0.11 and 3.78 l/min (0.03 and 1 US Gal/min). This means that although flow was detected below 0.11 l/min, flows in the very low end of the range (<0.11 l/min) may be slightly off. The test began with the tool positioned at the first depth of interest. Once three heat pulse triggers yielded the same values ( $\pm 0.08$  l/min or  $\pm 0.02$  USGal/min), the test continued, moving the tool to the next target depth. Five-to-ten minutes were given for the fluid to stabilize after the tool was moved in the borehole. In well PH-11-10, presumed gas emission interfered with the testing, requiring several tests to be performed at one depth. Minimum and maximum values for that depth were then displayed on the log figure.

Although upward flow in POH-11-06 exceeded the flow meter’s capacity, fluid logs and the caliper were successful in identifying the significant inflow zones in the open portion of the well. After fluid logging, the well collapsed at 23.9 m and image logs could not be collected in the lower portion of the borehole.

In well PH-02, no flows were detected under ambient conditions, so a pump test was performed to identify permeable intervals in the borehole. A Redi-Flo 2 Grundfos pump and controller were used to induce upward flow in the borehole. The pump was placed at 7 m depth, 3 m below the top of the water column. Flow rate was monitored every few minutes on surface using a graded bucket and a stopwatch, while water levels were measured in the borehole using a water-level meter. The flow rate was carefully adjusted to avoid exceeding the tool’s upper limit of 3.78 l/min (1.0 US Gal/min), and also to equalize the pumping rate with the recharge (i.e. no measurable drop in water level during the pumping). Once the pumping and water levels were stabilized in PH-02, the test began with the tool positioned at the first depth of interest at the bottom of the well, and moved upwards. The testing concluded with a final test a few metres below the pump, where the upward flow measured by the tool was equal to that of the pump.

### 3 PROCESSING

Logs from each borehole were imported into WellCAD borehole software and elevation scales were added into the log figures. Log completion details and information from the cuttings logs were incorporated into the dataset. Due to calibrations carried out in the field and/or lab prior to logging, very little processing was required for the stratigraphic and fluid logs.

Televiwer images were imported into WellCAD and oriented to magnetic north for structural interpretation. An acoustic caliper was calculated from the traveltime image using a fluid velocity corrected to the fluid temperature log. Structures were classified using the scheme developed for this project (Table 4). Dip angles of the structures were then corrected for minor borehole tilt (1-5° from vertical) as measured by the televiwer’s accelerometers.

Table 4 – Structural classification table.

Structure Type	Structure Sub-type	Sample Structure	Structure Code
Broken Zone	Evidence of flow	Intersecting fractures, weakened zone	BZ-F 
	No evidence of flow		BZ-NF 
Open Feature	Continuous/discontinuous fracture with aperture - evidence of flow	Open joint, open bedding partings	O-F 
	Continuous/discontinuous fracture with aperture - no evidence of flow		O-NF 
Closed Feature	Parallel	Bedding, foliation	Cpl 
	Perpendicular	High angle joints	Cpr 

## 4 INTERPRETATION AND ANALYSIS

Figures containing the interpreted log suite from each borehole can be found in Appendix I. To provide boundary conditions for the groundwater modelling, a set of site-wide parameters which summarized the geological and groundwater properties measured on site were also developed, and are discussed below.

### 4.1 Lithological Interpretation

To assess site-wide sedimentary rock conditions, lithological logs (gamma, resistivity, and magnetic susceptibility) were compared side by side using the elevation scale. The guard resistivity logs effectively identified an interval of elevated resistivity, the lower contact of which formed a sharp marker horizon (marker horizon 1) present in all the wells. This horizon could also be identified in the natural gamma logs as the top of a sequence of elevated natural gamma counts. A second sequence of upward increasing natural gamma counts topped by a sharp contact formed a second marker horizon (marker horizon 2). These, and other notable log features, could generally be traced from well to well in cross-section, and formed the basis for three units identified in Figure 2. Representative logs from POH-11-02 and POH-11-03 were chosen to form a “Geophysical Type Log”. Cuttings logs, provided by TechnoRem Ltd. of Laval, QC (TechnoRem, 2013), were used to summarize the materials found within each unit. When the core from the two cored boreholes will be logged, the results will enhance these descriptions.

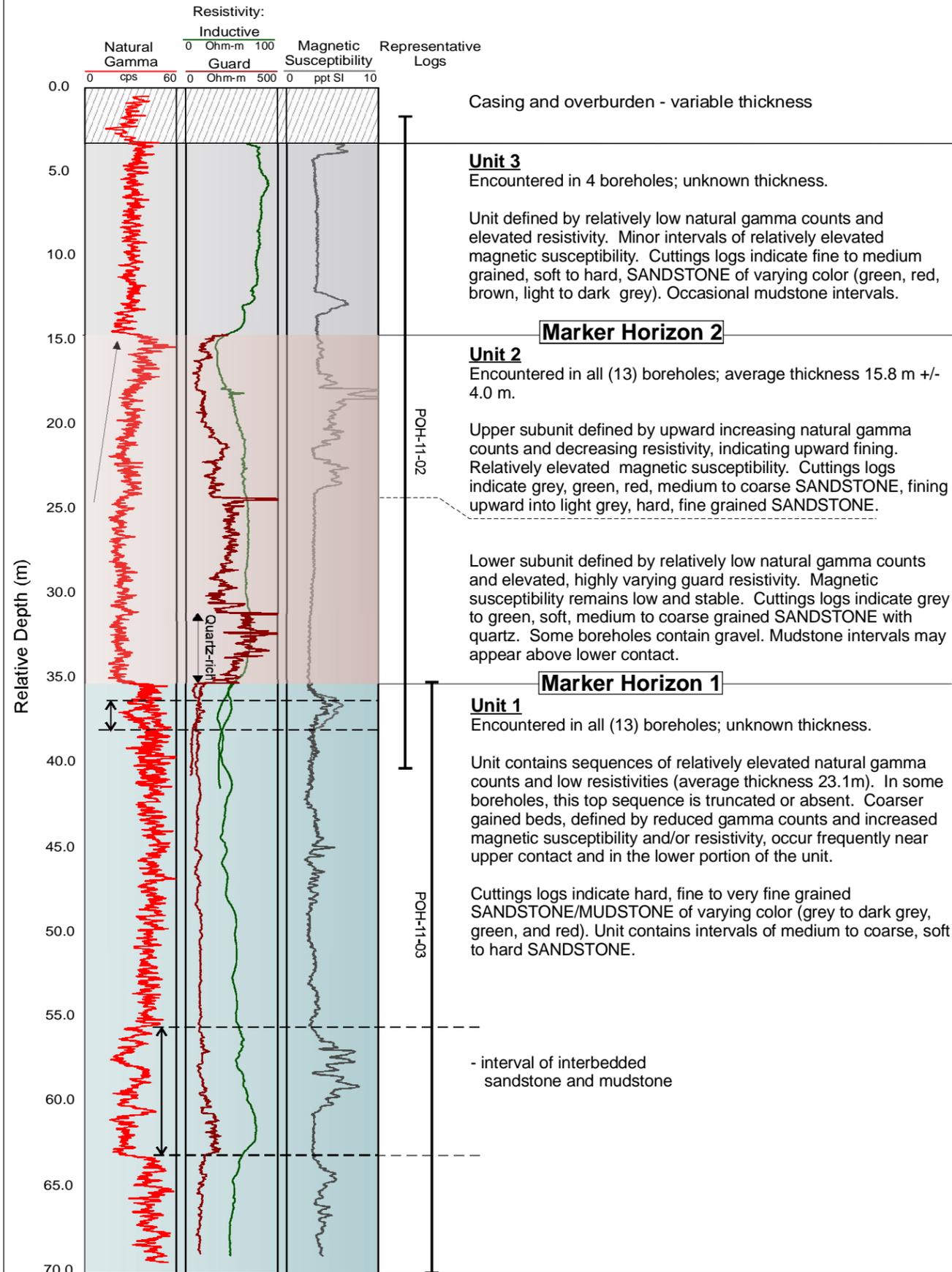
Unit 1, whose top is formed by marker horizon 1, is encountered in all 13 boreholes and is defined by relatively elevated natural gamma counts associated with very fine grained sandstones and mudstones. These rocks are described as hard and vary in color from light to dark grey, red, and green. A thick sequence of elevated natural gamma counts was often found at the top of this unit, averaging 23.1 m in thickness (where present), although it was truncated or absent in a few boreholes, suggesting the influence of erosion or possibly faulting. Coarser grained intervals, defined by a drop in gamma counts and an increase in resistivity and/or magnetic susceptibility, were observed near the bottom of the unit.

Unit 2, whose top is formed by marker horizon 2, is encountered in all 13 boreholes and is defined by relatively low gamma counts and elevated resistivities. The unit is approximately  $15.8 \pm 4.0$  m in thickness, and is divided into two subunits based on changes in the magnetic susceptibility logs and resistivity logs. The lower subunit is defined by a sharp lower contact and relatively elevated resistivity (marker horizon 1), associated with the quartz described in the cuttings logs. Mudstone intervals may be present above the lower contact. Magnetic susceptibility and natural gamma levels are low and very stable through this subunit. In the upper subunit, natural gamma counts increase / resistivities decrease upwards, indicating an upward fining sequence. Magnetic susceptibilities in this unit vary and are more elevated than in the underlying subunit.

Unit 3 is interpreted in only four boreholes. It is defined primarily by a sharp lower contact with Unit 2 (marker horizon 2), and relatively elevated resistivities. A stable natural gamma log suggests that this unit is fairly uniform in grain size. Cuttings logs describe this unit as fine to medium grained, soft to hard sandstone which varies in color (green, red, brown, and grey). Mudstone intervals are present.

Within each of these units, geophysical signatures vary from well to well in thickness and mineralogy/grain size, suggesting variability in depositional environment over short distances (<1 km). These results are in accordance with conditions expected in a fluvial environment.

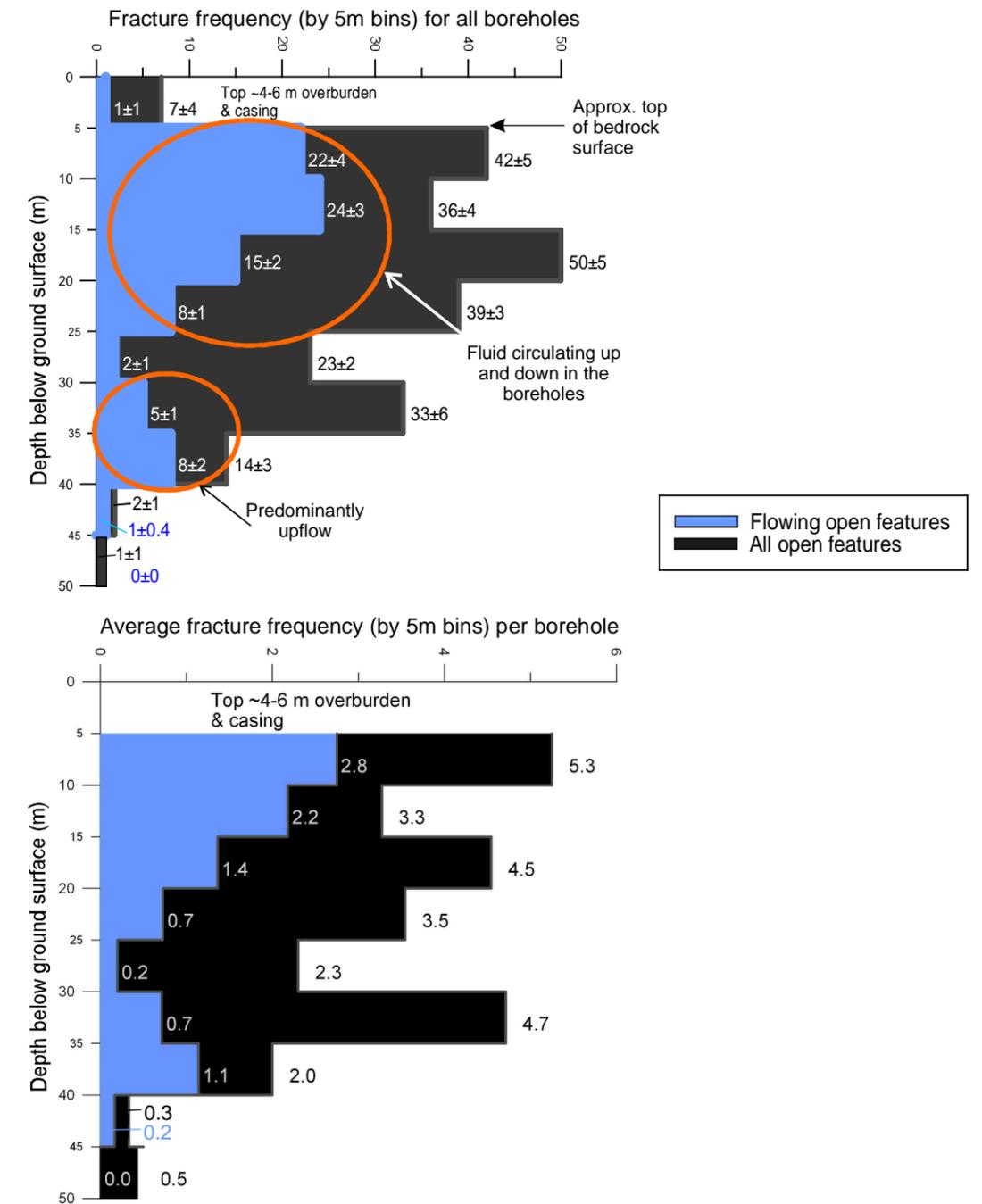
# Geophysical Type Section



# Fracture Frequency by Unit

Too few data in this interval (2 m of televiewer data in 1 borehole)	
All open/partially open features	0.70 / m
Open/partially open flowing features	0.35 / m
(153 m of televiewer data in 10 boreholes)	
All open/partially open features	0.73 / m
Open/partially open flowing features	0.12 / m
(172 m of televiewer data in 10 boreholes)	

# Fracture Frequency by Depth



**FIGURE 2**  
 Geological units and fracture frequency

Haldimand, Gaspé, Québec  
 Nov 2012

Open File 7492  
 Geological Survey of Canada



Figure 2 also shows fracture frequency ‘by Unit’ and ‘by depth below ground surface’. Open features (fractures) are described as either “open - not flowing”, or “open - flowing” based on the interpretation of fluid logs (see Section 4.3). When interpreted by Unit, flowing fractures are, on average, 3 times more common in Unit 2 than in Unit 1, likely because Unit 1 is deeper than Unit 2. To study whether depth may have a greater influence on fracture frequency than lithology, fracture frequency was also plotted as a function of depth. Since not all boreholes reached 50 m depth, the average number of fractures per 5-m bin per borehole was calculated to remove sample bias in the shallower depths. In both cases, trends indicate that there is a significant drop in ‘open’ and ‘open and flowing’ fractures below 40 m. As elevation of marker horizons varies across the site, this suggests that fracture patterns are primarily controlled by depth below rock surface, and not as closely related to elevation or geological unit, although geological unit certainly has some influence.

#### 4.2 Structural Interpretation

Planar structural features interpreted from analysis of oriented televiewer images were plotted as poles on stereonet after plane projection on the upper hemisphere of an equal-area Schmidt diagram (Figure 3). Features were corrected for the tilt of the borehole (generally between 0.5° – 5° from vertical) prior to analysis, and dips are presented relative to horizontal, and azimuths relative to magnetic north. Stereonets are shown in Figure 3, and Table 5 presents the summary statistics grouped by Unit number.

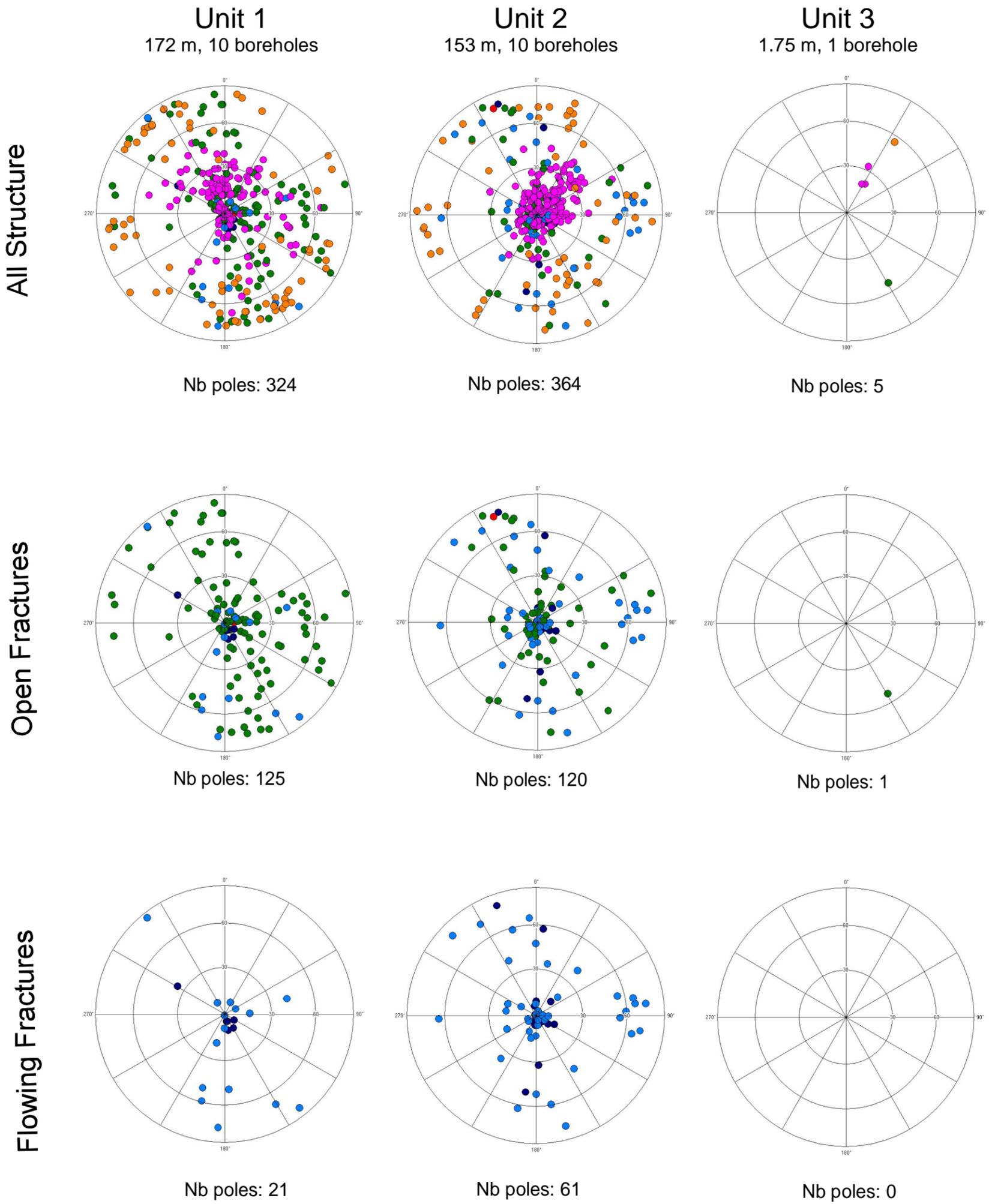
Table 5 – Mean azimuth and dip angles based on stereonet analyses (refer to Table 4 for feature acronyms).

Feature Type	Unit 1			Unit 2		
	Mean Azimuth (°)	Mean Dip (°)	Nb. features	Mean Azimuth (°)	Mean Dip (°)	Nb. features
BZ-F	196	4	6	133	4	17
BZ-NF	87	4	2	343	37	2
O-F (all angles)	162	25	15	82	5	44
O-NF (all angles)	103	16	102	89	2	57
Closed ~ low angle (Cpl)	13	9	126	49	7	192
Closed ~ high angle (Cpr)	149	81	73	162	70	52

Broken zones (BZ) are defined in this study as structures which are continuously fractured over 0.3 vertical metres or more, and exhibit significant aperture in the caliper log (>25 mm beyond the nominal borehole diameter at some point within the broken zone). These features were relatively few and could be difficult to analyse due to their non-planar expression on the borehole wall. They tend to be relatively low dipping features which are a result of cross-cutting or closely spaced fractures which were further damaged or washed out by drilling.

Closed planar (Cpl) features are primarily low angle (mean dips 7° - 9°) in both Units 1 and 2, with a NW scatter trend in Unit 1, and a NE scatter trend in Unit 2. This scatter may be a result of changes in depositional environments, or a consequence of later regional deformation. Closed steeply dipping features (Cpr) were of similar mean orientations in both Units 1 and 2 (149°/81° and 162°/70°, respectively) suggesting that joint patterns may be a product of regional or near-surface stress

# Polar Projection of Dip Direction Equal Area, Northern Hemisphere



### Pole Legend

- Broken zone - flow interpreted
- Open fracture - flow interpreted
- Broken zone - no flow detected
- Open fracture - no flow detected
- Closed feature - parallel
- Closed feature - perpendicular

### Fracture frequency by unit

	Unit 1	Unit 2	Unit 3
Open feature	0.73 / m	0.70 / m	sample size too small
Open & flowing	0.12 / m	0.35 / m	

FIGURE 3  
Structure by Unit

Haldimand, Gaspé, Québec  
Nov 2012

Open File 7492  
Geological Survey of Canada



conditions and not strictly unit dependent. However, the significant scatter in these features also suggests that intrinsic heterogeneity exists in the geologic formations, in agreement with a fluvial origin.

Open features (O) have dips which are low angle ( $0^{\circ}$ - $30^{\circ}$ , 52% of open features), moderate angle ( $30^{\circ}$ - $60^{\circ}$ , 26% of features), and high angle ( $60^{\circ}$  –  $90^{\circ}$ , 24% of open features). Approximately 33% of open fractures are flowing (O-F, BZ-F), and these are a subset within the open features. Features interpreted as flowing (see following section) are usually low angle ( $0^{\circ}$  -  $30^{\circ}$ , 57% of flowing features). Moderate angle ( $30^{\circ}$  -  $60^{\circ}$ , 25% of features) and high angle ( $60^{\circ}$  –  $90^{\circ}$ , 18% of open features) represent 43% all flowing features. These results indicate that fractures which transmit fluid are mainly (sub)-horizontal in the upper 35 m of the rock surface.

### 4.3 Fluid Analyses

A summary of fluid properties is presented in Table 6 and Figure 4. Ambient groundwater flow was detected in all wells except PH-02. Flow entering or exiting the borehole through fractures was interpreted where the flow meter measured a change in fluid flow above/below an open feature, and where the fluid logs measured a corresponding change in temperature and/or conductivity. Minor permeable features were also interpreted where small changes in temperature or conductivity were observed, even if flow was not measured by the flow meter, (i.e. minor flow below 0.03 Gal/min). Flowing fractures were totaled over 5 m intervals and plotted as fracture frequency logs next to the structure column of each borehole figure in Appendix I. Figure 4 shows that the rock mass is fractured primarily in the upper 35 m of the rock surface, but that the flowing features are concentrated in the upper 20 m, with a small increase between 25 and 35 m.

Table 6 – Summary of fluid values for each logged well. Temperatures from cased wells not shown in Figure 4 as casing may influence temperatures.

Borehole	Flow direction	Max Flow measured (l/min)	Gas observed?	Conductivity range ( $\mu$ S/cm)	Temp. range ( $^{\circ}$ C)
PH-02	no ambient flow measured	Upward induced 3.0	no	22 - 105	6.4 - 10.6
PH-01	up	0.64	yes	25 - 1567	7.1 - 8.7
POH-11-03	up	3.67	yes	70 - 85	6.9 - 7.0
POH-11-06	up	87 l/min after 24 h on October 26 – 27, 2012 (TechnoRem, 2013)	no	783 - 9940	-0.6 - -0.5
POH-11-10	up	0.77	yes	2063 - 33055	6.7 - 7.4
POH-11-12	up	0.12	yes	40 - 130	6.4 - 8.2
POH-11-14	up	0.13	no	140 - 1100	6.4 - 8.4
POH-11-05	down	3.07	no	-	6.6 - 8.6
POH-11-09	down	0.20	no	36 - 120	7.0 - 8.8
POH-11-02	down and up	0.22 down, 0.09 up	no	50 - 145	6.5 - 7.0
PH-04	N/A - PVC cased				6.6 - 9.0
POH-11-04	N/A - PVC cased				6.5 - 10.4
POH-11-15	N/A - PVC cased				4.0 - 5.7

# Fluid properties versus fracture frequency

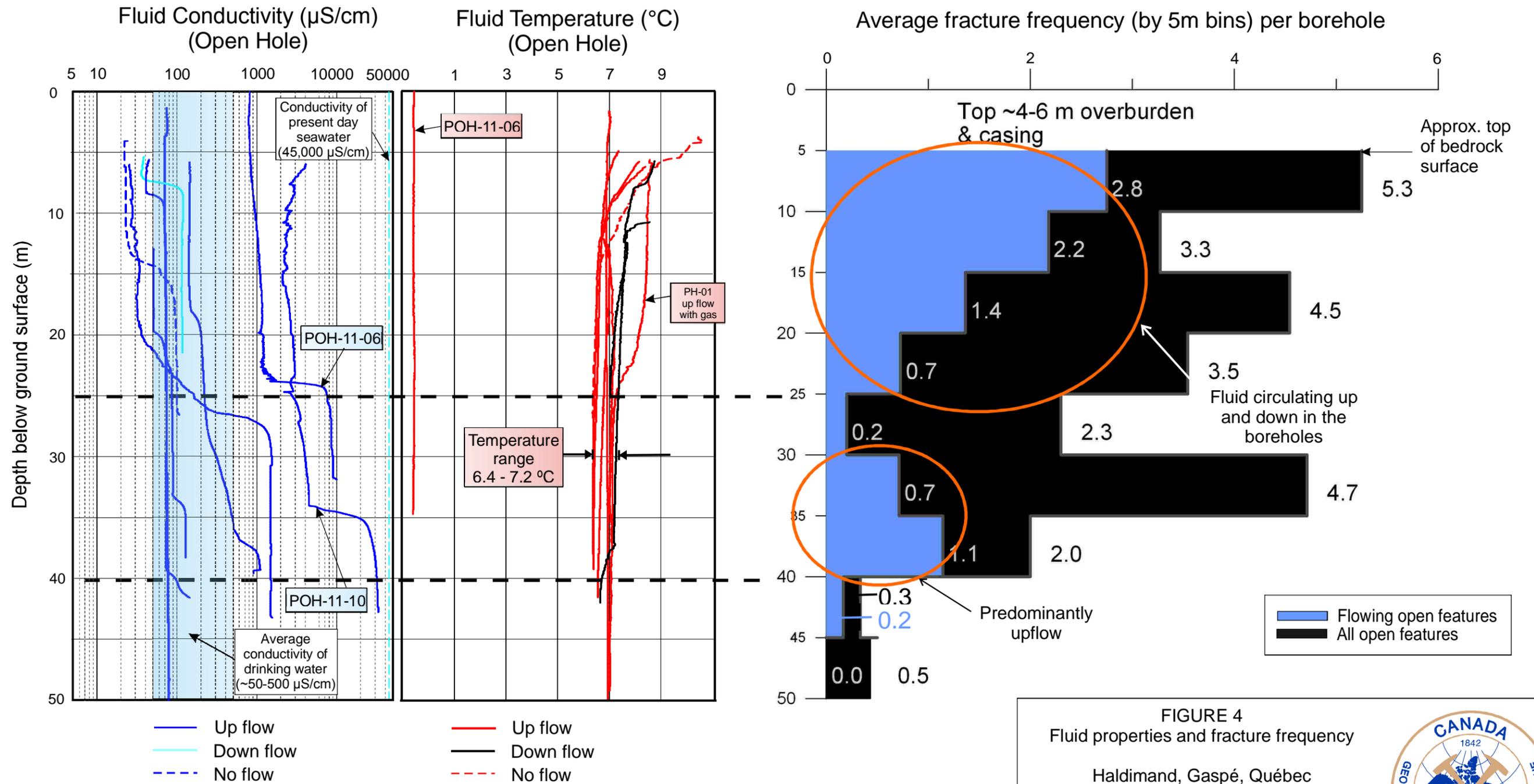


FIGURE 4  
Fluid properties and fracture frequency

Haldimand, Gaspé, Québec  
Nov 2012

Open File 7492  
Geological Survey of Canada



### 4.3.1 Temperature

Fluid logs indicate that the average groundwater temperature ranged between 6.4 and 7.2°C, and generally decreased with increasing depth. However, temperatures were slightly more elevated (7.3 – 7.6°C) in the two down-flowing wells in the upper 25 m, suggesting a rapid recharge connection with warmer surface waters (heavy October rainfall). Below 25 m, temperatures become more uniform, an observation in agreement with the bulk of the fluid flow occurring in the upper 20 m of the rock surface (see Figure 4).

Notable temperature anomalies were present in PH-01, PH-02, and POH-11-06. In the interval between 6 and 24 m, temperatures were more elevated in PH-01 than other wells at these depths (reaching 8.7°C) and may have been influenced by the presence of gas bubbling to surface. In PH-02, the interval between 4.0 and 5.6 m corresponds to the most elevated temperatures among all the boreholes. As ambient flow greater than 0.11 l/min was not interpreted in this well (i.e. “no flow” detected by flow meter), fluids in the top 1.6 m of the water column were more influenced by air temperatures. In POH-11-06, fluid from fractures at and below 23.9 m was rising to surface at very elevated flow rates (reported by TechnoRem as 87 l/min after a 24-h flowing period on October 26-27, 2012). This fluid was measured at temperatures between -1 and 0°C, a condition which is very difficult to explain, other than possible tool malfunction. As the thermistor in this temperature tool behaves non-linearly approaching 0°C, a careful tool recalibration in an ice bath was performed in the lab post survey and data were back calibrated to check the results. Lab calibrations indicated the tool was working normally. It is possible that results may have been influenced by borehole conditions (elevated fluid velocities, pressures, and conductivities) and interfered with temperature sensors.

### 4.3.2 Fluid Conductivity

Although most conductivities are low (i.e. <200 µS/cm), values in the flowing portions of the wells across the site ranged from <20 µS/cm (i.e. POH-11-02, PH-01) to 1000 – 2000 µS/cm (i.e. POH-11-06, POH-11-10 respectively). Electrical conductivities in up-flowing wells POH-11-06 and POH-11-10 indicate that surficial groundwater has mixed with more conductive fluids at depth which are rising to the surface. Their origin, chemistry, and age are a topic of research in the INRS hydrogeological site study.

It was common to see an increase in conductivity in the non-flowing interval at base of a well. This could be caused by an increase in fines content settling to the bottom of the well, and could be identified by a clouding of fluid in the video logs (i.e. POH-11-02, and -14 where electrical conductivities in this interval range between 130 – 1100 µS/cm). In absence of up-flowing high conductivity groundwater, there may also be a connection between the finer grained sedimentary rock of Unit 1 and a small (i.e. ~100's µS/cm) increase in fluid conductivity, although this may be a consequence of Unit 1 being in the base of the hole.

In wells POH-11-06 and POH-11-10, however, the fluid in the base of the well was clear in appearance but conductivities were more elevated than in other wells. Conductivities at the base of POH-11-10 rose to 33,000 µS/cm, and conductivities at the base of POH-11-06 rose to 9,900 µS/cm (although this well collapsed before the video camera/televIEWER could be lowered into the base of the well). POH-11-06 is located in a topographic depression and may be associated with a deep discharge zone influenced by more saline (and possibly older) groundwater. POH-11-10, however, is located on the shoulder of a local topographic high where upflows may be structurally as well as topographically controlled. The influence of upward flowing pathways on salinity is one of the themes being

researched and modeled by INRS using all 89 groundwater samples collected at the sites shown in Figure 1 (see Raynauld et al., 2012).

#### 4.3.3 *Flow Meter*

In all but one borehole, the flow meter measured upward or downward flow ranging between 0.04 and 3.67 l/min. Table 6 presents the directions and maximum magnitudes of flow measured, while log figures in Appendix I present the individual interpretations of the flowing intervals in each well. As flows are ambient, the data does not represent how transmissive the fractures are, but how much flow was moving through the fracture system at the time of testing. Zones of localized discharge can be identified by the up- flowing wells.

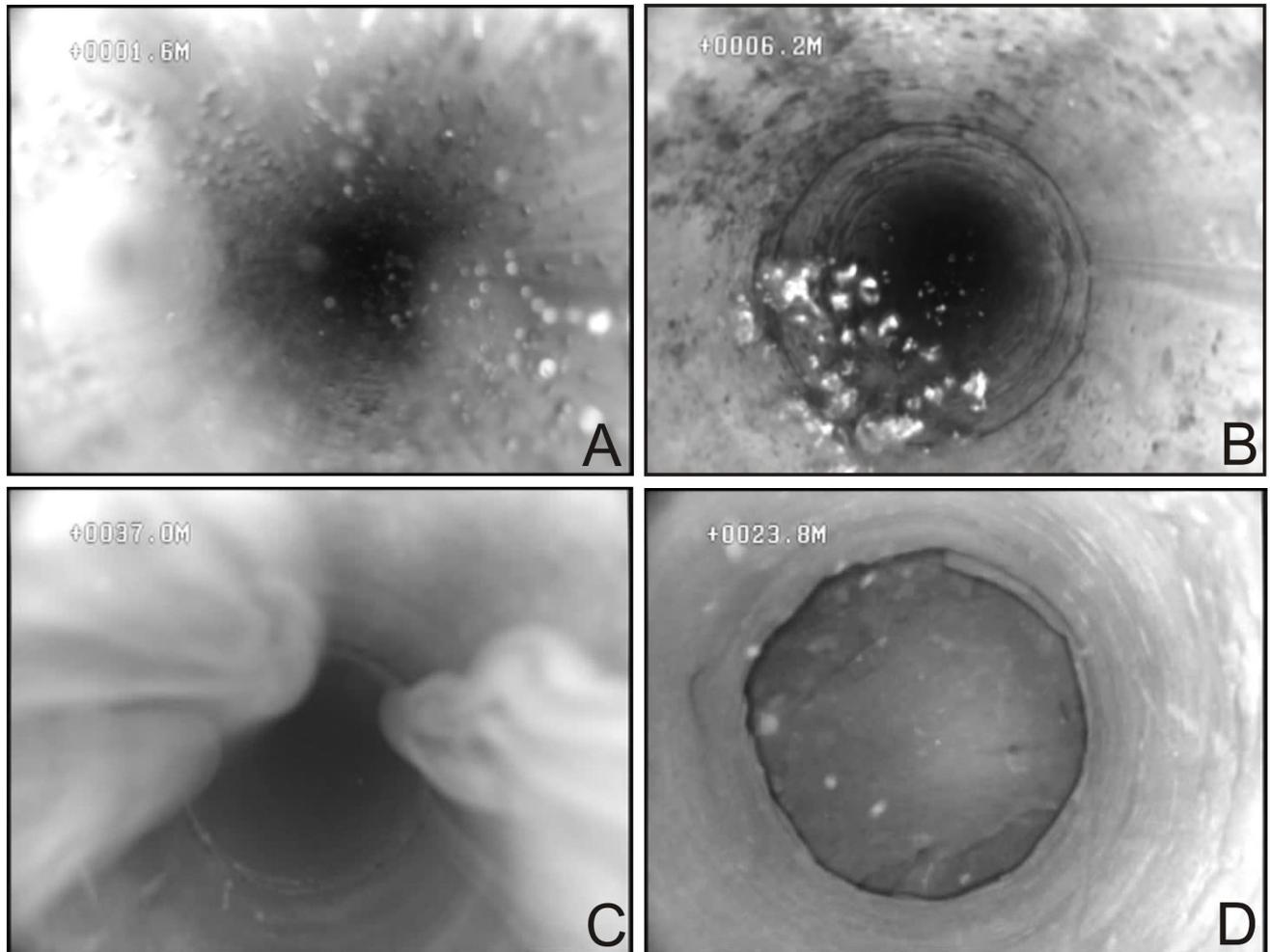
As shown in the upper 6 m of borehole PH-02, a “no- flow” measurement by the flow meter (i.e. <0.04 l/min) does not necessarily mean that the zone is not transmitting small volumes of flow. Within the broken zone spanning 4.60 – 6.70 m depth, there is a 1.0°C drop in fluid temperature, indicating that cooler fluids are entering the borehole through this zone at very low flow rates under ambient conditions. A pumping test in this well helped to identify the transmissive fractures in the well. This indicates why the sensitive fluid temperature and conductivity logs are so important for the detection of very small volumes of fluid flow in these studies.

#### 4.3.4 *Video Logs*

Video log recordings in each borehole provided moving images of features which would otherwise not have been captured. The images were particularly useful in detecting the presence of apparent gas bubbles in up-flowing wells PH-01, POH-11-03, -10, and -12 (Figure 5). What appeared as gas ranged in appearance from small clear single bubbles at infrequent intervals (POH-11-12) to relatively large bursts of gas (PH-01), to fast flowing small clear and black bubbles (POH-11-10). In borehole POH-11-03, upward flowing trails of what appeared like “smoke” floated upwards, generally not mixing with the water column. This may be caused by fine dissolved gas bubbles, although it could also be related to mud forced into the fractures during drilling earlier in the fall or some other naturally occurring fine grained material flowing along open fractures in the rock mass. The analysis of methane gas in groundwater is needed to provide firmer indications that the features seen on the video log are gas bubbles.

Video logs also captured images of water entering some of the boreholes above the water table. Partially open fractures (those which do not extend completely around the borehole) convey water into the borehole, showing that fractures which are transmitting groundwater to/from the borehole do not need to be completely open or planar.

Upward flowing features



Downward flowing features

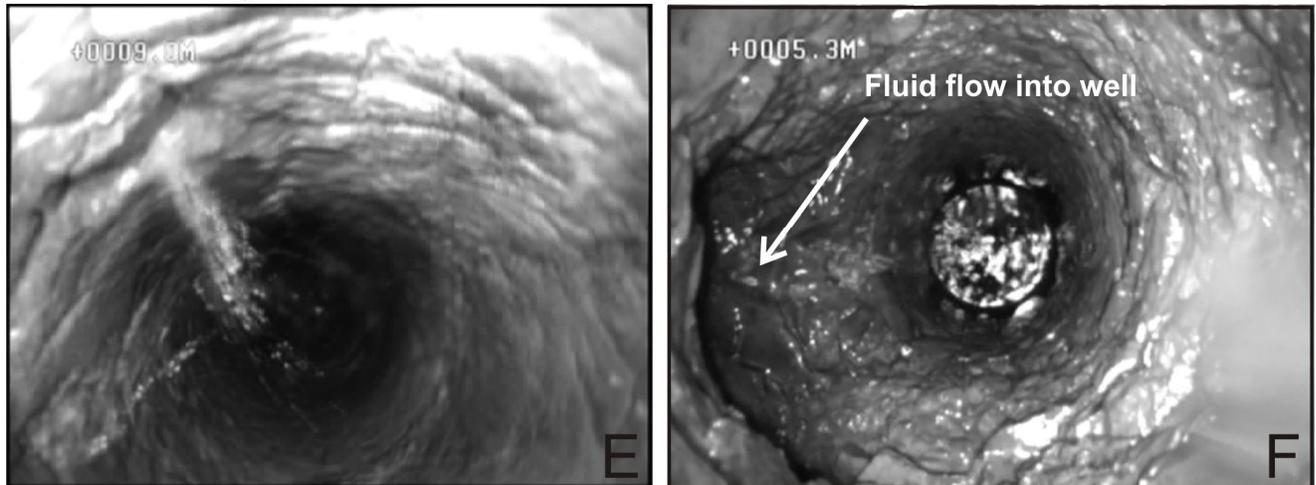


Figure 5 – Video still images of fluid flow in wells. A) Continuous bubbling in POH-11-10. B) Gas burst in PH-01. C) Trails of fine material entering borehole in POH-11-03. D) High volume flow in POH-11-06 right above caved-in fracture zone. E & F) Flow entering borehole above water table in POH-11-05 (E) and PH-01 (F).

## 5 SUMMARY

Geophysical logging in 13 boreholes at the Haldimand site provided a suite of logs which have helped in the hydrogeological characterization of the rock stratigraphy, structure, and fluid properties.

Lithological logs, and in particular, the guard resistivity logs, were effective in identifying variations in geological strata which can be correlated from well to well through two identified marker horizons. The logs were also used to develop a representative 'type section' of geophysical properties in the upper 50 m of the sedimentary rock sequence, and to distinguish three lithological units. While these units show gamma/resistivity trends, variable tool response can be seen from hole to hole. This is consistent with deposition in a fluvial environment, as there is local variability in unit thicknesses and grain sizes over horizontal distances of less than 500 m.

Fluid and televiewer logs indicate the top 0 - 35 m of the rock exhibit open/partially open fractures, and all open (uncased) boreholes but one were found to be naturally up- or down-flowing at the time of logging. Fluid temperature and fluid conductivity logs together were extremely effective in identifying fractures which were transmitting fluid into, or out of, the borehole. Follow-up flow meter tests above and below these depths indicate up/down flows range between 0.04 – 3.67 l/min (with the exception of one well which is upward flowing at 87 l/min). These up- and down-flow trends in the wells agree with groundwater recharge and discharge zones as interpreted from the piezometric map obtained with groundwater level measurements in the wells. A drop in fluid flow levels during the course of field work appears to correlate with decreasing precipitation levels. This suggests a rapid connection between surface recharge zones and the entire aquifer, as well as links between the aquifer and local streams. This observation is in also agreement with warmer groundwater temperatures in the highly fractured upper 20 m of the rock surface.

Video logs were an important addition to the fluid log suite. In four of the up-flowing wells, apparent gas bubbles (type and origin currently unknown) ranged in appearance from small clear single bubbles at infrequent intervals, to relatively large bursts of bubbles, to fast-flowing small clear and black bubbles, and finally, to upward flowing trails of fine particles and/or gas. Analyses of dissolved gas concentrations in groundwater will provide firmer evidence of the nature and origin of these bubbles.

Nearly 700 structural features in the hammer-drilled and cored boreholes were identified in the televiewer logs. These structures were classified based on a system developed for this project and plotted as poles on stereonet relative to magnetic north. When interpreted with fluid log data, approximately 33% of open features are found to be flowing, and of these, 57% are dipping between 0° - 30°, and 25% are dipping 30° - 60°, indicating that the majority of the fractures which transmit fluid are horizontal-to-moderately dipping, and most are found in the upper 20 m of the rock surface. Only 18% of structures transmitting fluid in the top 40 m of the rock surface are steeply (>60°) dipping.

Figures 2, 3, and 4 present a site-wide summary of the lithological and structural conditions by unit, and groundwater conditions by depth in the upper 50 m of the ground surface. These parameters will help better understand the groundwater flow system in this region and will support the development of the groundwater numerical model.

## 6 DISCUSSION

### 6.1 Depth or Elevation? What is the Main Influence on Lithology and Groundwater Flow?

Plotting guard resistivity logs at the same elevation scale indicates that there are commonalities among the geological units based on elevation. However, a plot of fracture frequency versus depth shown alongside fluid logs versus depth (Figure 4) suggests that the fluid and fracture patterns are primarily influenced by depth below rock surface (subcrop), and are not as closely related to elevation, geologic unit, or sea level (as in the case of the fluid logs; see Figure 6). Flowing fractures could be found in either Units 1 or 2 (Unit 3 is cased, so direct measurements could not be made) and were not solely controlled by unit or geological material. However, when borehole data from all 13 holes are analysed, flowing fractures are, on average, 3 times more common in Unit 2 than in Unit 1 because Unit 1 is deeper than Unit 2 – therefore, fracture frequency is reported as both “by depth” (by 5 metre bin sizes), and “by unit” (see Figure 2).

Figure 6 shows that fluid temperatures converge on 7.0°C with depth, but that proximity to sea level does not clearly lead to an overall increase in fluid conductivity (i.e. sea water infiltration). The elevated fluid conductivities in POH-11-06 and POH-11-10 both terminate above sea level (14 m and 33 m, respectively). However, the deepest well, POH-11-03, is up-flowing with low conductivities (<100  $\mu\text{S}/\text{cm}$ ) along the entire well, indicating that upward gradients do not necessarily lead to high fluid conductivities. These observations reflect varying discharge and recharge zones across short distances on site, and that the properties of the fluids in the discharge (up-flowing) wells are not elevation dependant in the near surface which is fractured and heterogeneous. Conditions would likely become more homogenous with decreasing elevation as the deeper groundwater regime becomes predominant.

### 6.2 Faulting as a Structural Control?

To date, the geochemical results seem to be well related to the length of flow paths (Raynauld et al., 2013). This does not preclude some possible structural control on upflow, however. The presence of high pressure upward flows in borehole POH-11-06 (87 l/min), and elevated fluid conductivities in POH-11-06 and POH-11-10 suggests the possibility of structural controls in the rock, which are forming pathways that are bringing deeper, more conductive fluids to surface. Additionally, truncation of Unit 1 may be present in boreholes -05, -14, and -15, however, lithological variation inherent in a fluvial sequence makes faulting difficult to determine from lithological logs alone.

At this stage, any conclusion on faulting would be premature, and much more work is needed to assess the primary controls on groundwater movement in the rock. More detailed modeling, and possibly site drilling or seismic profiling would be required to assess the prevalence of near-surface faulting throughout the study area.

### 6.3 Recommendations for Future Similar Projects

An element of this project for the GSC involved assessing the most effective downhole tool suite for hydrogeological studies focusing on potential groundwater impacts from hydrocarbon exploration and/or production.

In open rock, lithological variations were well defined by a combination of the natural gamma, (guard) resistivity, and magnetic susceptibility tools. Induction resistivity logs lacked the vertical resolution

needed for cm-scale logging, however, they were necessary in PVC-cased holes to assess lithological variations together with the natural gamma logs, and correlate the logs from hole to hole.

Fluid logs (temperature *and* conductivity) are key in the detection of fluid movement in the wellbore, and, at this site, in the assessment of conductive (saline) groundwater flowing upward from greater depths. These logs are especially important in areas of very low flow (i.e. below the detection limit of a flow meter).

At this site, ambient flows were measured in all but one borehole. However, the relative amount of ambient flow entering/exiting the borehole cannot be used to estimate the fracture transmissivity (T), and thus the hydraulic conductivity (K) of the media. This is particularly true here where recharge rates are closely tied to precipitation, which changed from day to day and decreased throughout the course of the three week fieldtrip. If, however, flow is measured under two relatively steady conditions (i.e. ambient and pumped flow), a transmissivity can be estimated (Paillet, 1998). Ambient and pumped logging would need to be conducted together at future well sites for T or K estimation.

The acoustic televiewer logs were very effective in the assessment of structural orientations in the fluid-filled portion of the boreholes, and allowed for the calculation of 360° caliper logs. For future work, the addition of an optical televiewer (with true color images) would enhance structural and lithological analysis, and would provide images above the water table. This would lead to a more representative structural dataset in the key fractured interval (0 - 20 m) below the top of rock.

The video log proved to be very important for observing groundwater movement and gas flow within the well. Images also indicated where fluid became cloudy in the base of the well, and provided a picture of borehole conditions above and below the water surface (i.e. ooze on walls, broken zones, and fracture continuity into the walls). The pictures significantly enhanced the interpretation of the fluid and ATV logs, and allowed for the identification of bubbles in the wells, which would have otherwise gone undetected.

Although not used here, downhole sonic logs would also have been very helpful by providing compressional (P) and shear (S) wave velocities in the rock mass surrounding the boreholes. Using  $V_p$  and  $V_s$  in combination has been used successfully to look at variation in lithology and porosity (Hearst et al, 2000).

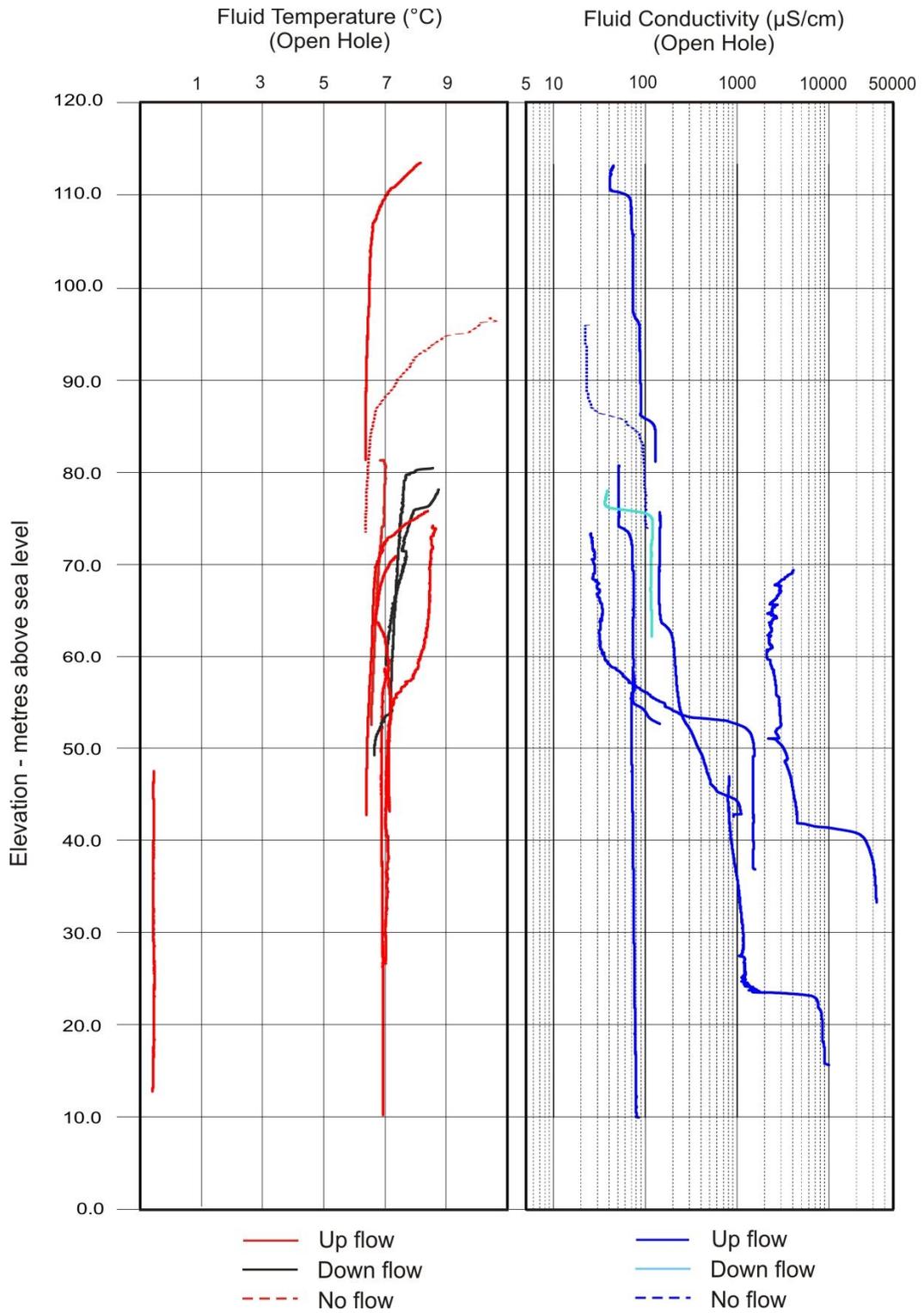


Figure 6 – Fluid temperature and conductivity versus elevation in all 13wells.

## ACKNOWLEDGEMENTS

The authors would like to acknowledge the contributions of Pétrolia who granted permission to NRCan to access their observation wells and cores, which were drilled for this study by TechnoRem Inc. The authors also acknowledge TechnoRem who provided the geological and well completion data for this report. Funding for the downhole geophysical logging was provided by the Environmental Geoscience Program of Natural Resources Canada. With our thanks to Dr. Christine Rivard for her review of this report.

## REFERENCES

- Desbiens, S., 1990. La formation de York River de la région de Gaspé : un complexe deltaïque. Commission Géologique du Canada, Québec, Dossier public 2235, p.21-22.
- Hearst, J.R., Nelson, P.H. and Paillet, F.L., 2000. Well Logging for Physical Properties; John Wiley and Sons Ltd., England, 483 p.
- Pétrolia, 2013a. <http://haldimand.petroliagaz.com/imports/medias/pdf/Communiqués-presse/2009-10-22-fr-petrolia-devoile-premiers-resultats-haldimand2.pdf> <accessed Nov 2013>
- Pétrolia, 2013b. <http://www.petroliagaz.com/imports/medias/pdf/2013-01-31-depliant-fr.pdf> <accessed Nov 2013>
- Raynauld, M. Crow, H., Fagnan, N.; Lefebvre, R.; Molson, J. Gloaguen, E.; Benoit, N. 2013a. Caractérisation des conditions hydrogéologiques au-dessus du réservoir pétrolier de Haldimand, Gaspé, Québec; *In proceedings: GéoMontreal 2013 - 66th Annual Canadian Geotechnical Conference and 11th Joint CGS/IAH-CNC Groundwater Conference*, Montreal, Canada, September 29<sup>th</sup> - October 3, 2013
- Raynauld, M., Lefebvre, R., Crow, H., Gloaguen, E., Ahad, J., Molson, J. 2013b. Caractérisation hydrogéologique du secteur Haldimand: Phase initiale. Rapport Intérimaire. Institut national de la recherche scientifique (INRS) – Centre Eau Terre Environnement, Rapport de Recherche R-1459, Octobre 2013.
- TechnoRem Inc., 2013. Caractérisation hydrogéologique des secteurs Haldimand et Tar Point, Gaspé, Québec, Phase I, Rapport préliminaire, Réf. : PR11-92, juin 2013, 121 p. plus annexes.

## APPENDIX I

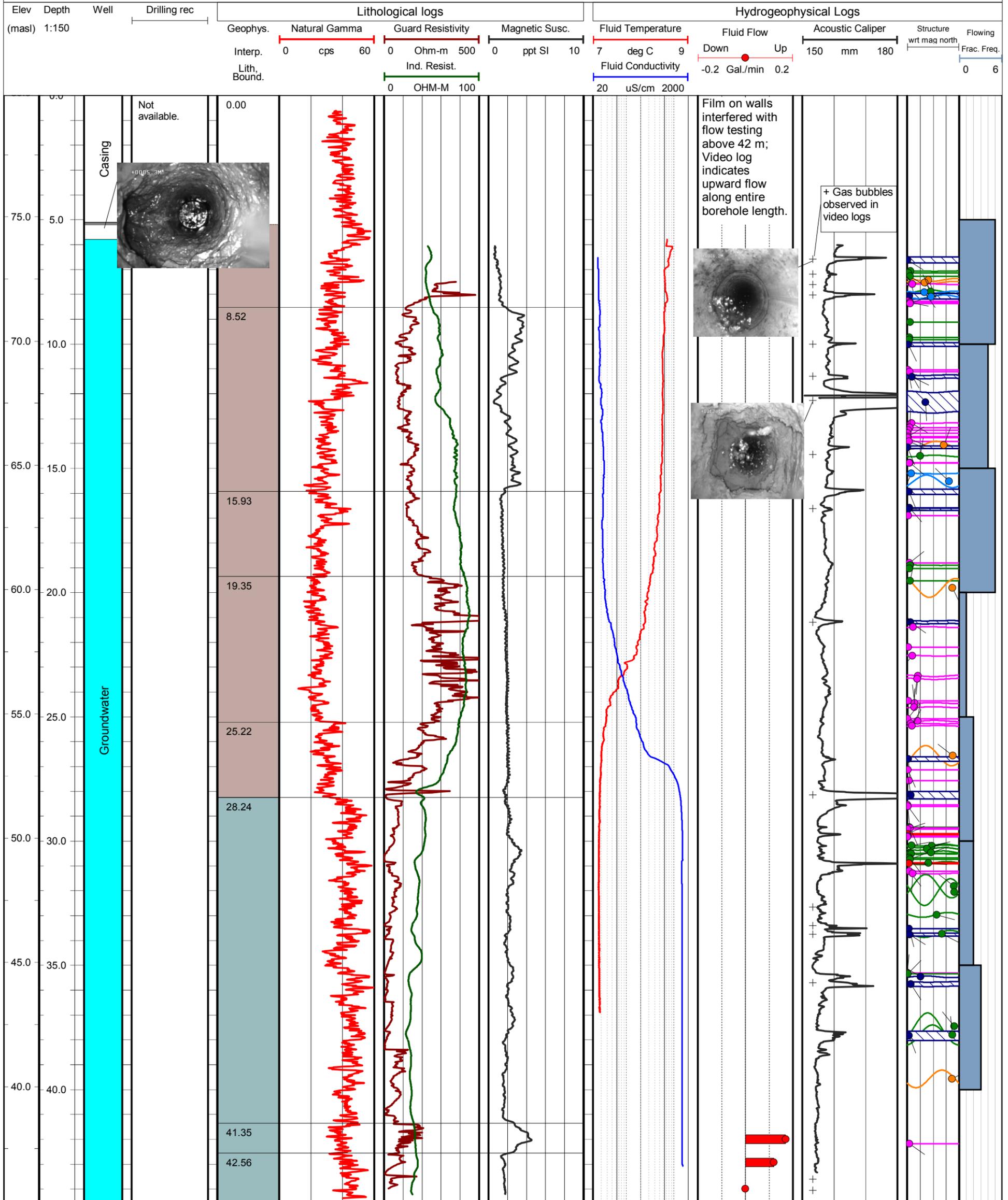
### Interpreted Geophysical Log Suites

Borehole: PH-01  
 Location: Haldimand, QC  
 Project: Groundwater Asmt.  
 Study Area: Gaspésie, QC

Easting: 395 520 m  
 Northing: 5 406 827 m  
 UTM Zone: 20  
 Datum: NAD 83

Date Drilled: 2005  
 Method: Hammer  
 Diameter: 152 mm  
 Depth: 44.5 m

Date Logged: 8-10-Nov-'12  
 Water Level: 5.79 m  
 Logged By: GSC  
 Log Ref: Soil Surface

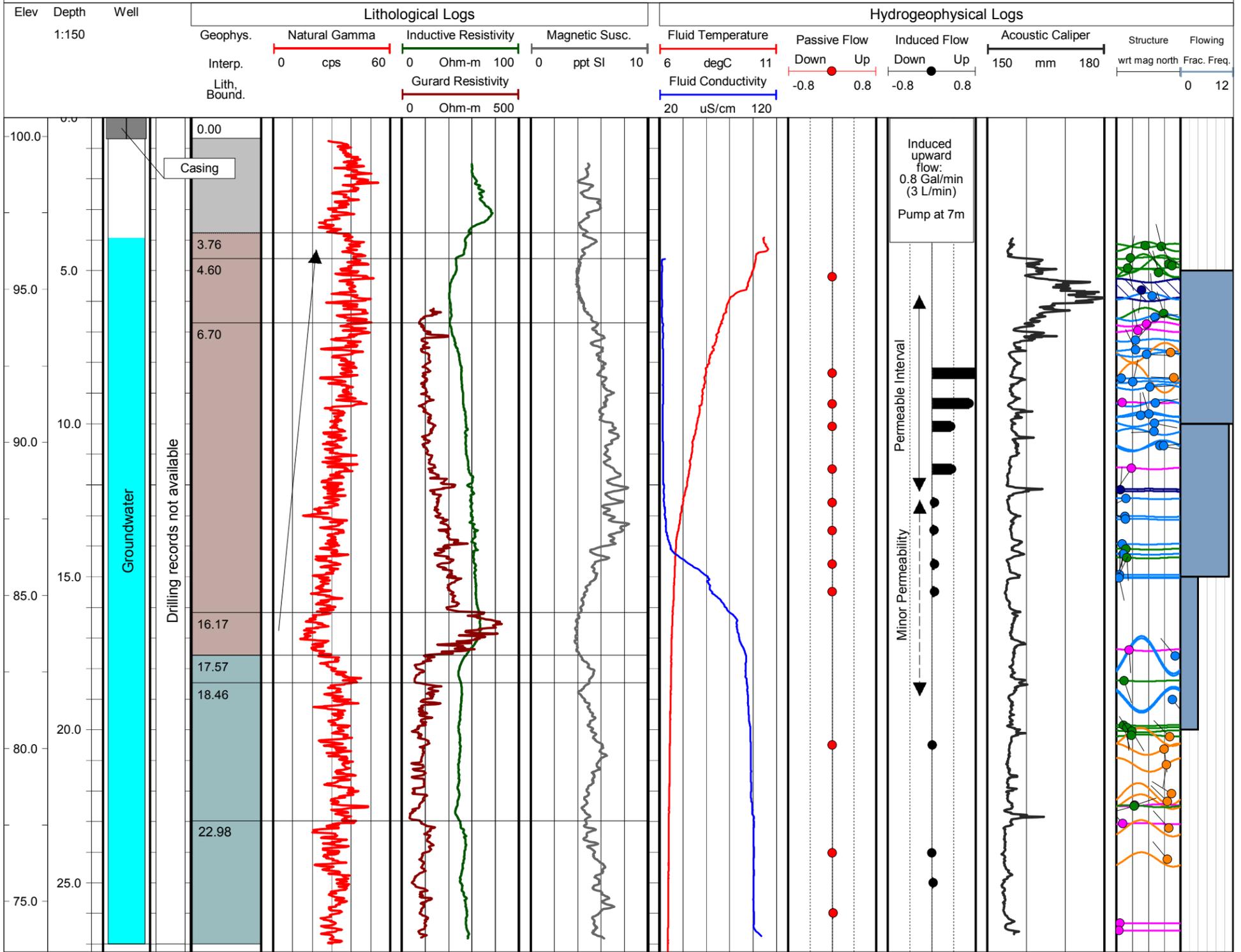


Borehole: PH-02  
 Location: Haldimand, QC  
 Project: Grndwater Asmt  
 Study Area: Gaspésie, QC

Easting: 394 660 m  
 Northing: 5 407 212 m  
 UTM Zone: 20  
 Datum: NAD83

Date Drilled: N/A  
 Method: Hammer  
 Diameter: 152 mm  
 Depth: 27 m

Date Logged: 14,15-Nov-'12  
 Water Level: 3.93 m  
 Logged By: GSC  
 Log Ref: Soil Surface

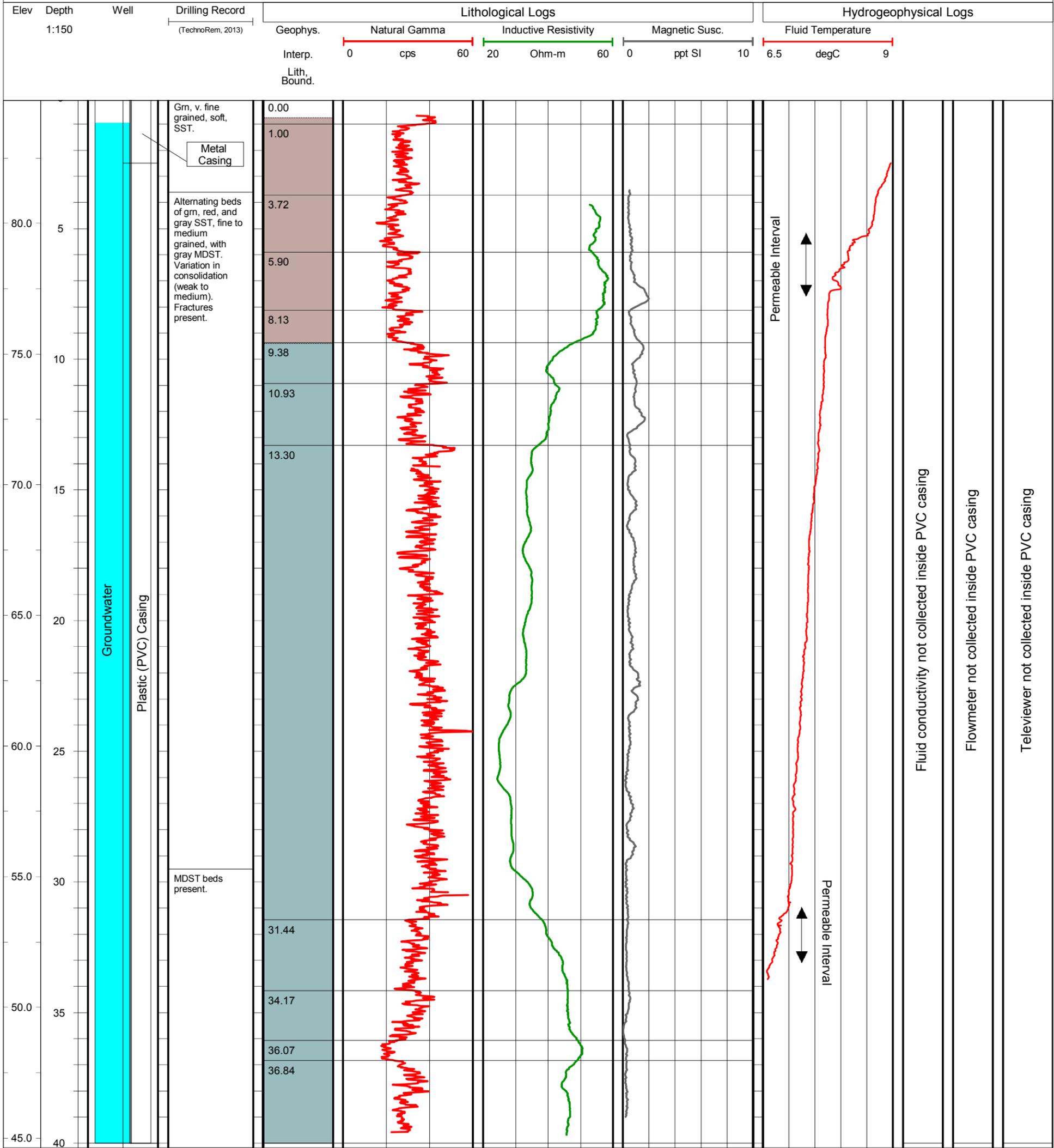


Borehole: PH-04  
 Location: Haldimand, QC  
 Project: Grndwater Asmt  
 Study Area: Gaspésie, QC

Easting: 393 956 m  
 Northing: 5 407 759 m  
 UTM Zone: 20  
 Datum: NAD83

Date Drilled: 2-Oct-'12  
 Method: Rot. Perc.  
 Diameter: 152 mm  
 Depth: 40.18 m

Date Logged: 2-Nov-'12  
 Water Level: 0.96 m  
 Logged By: GSC  
 Log Ref: Soil Surface



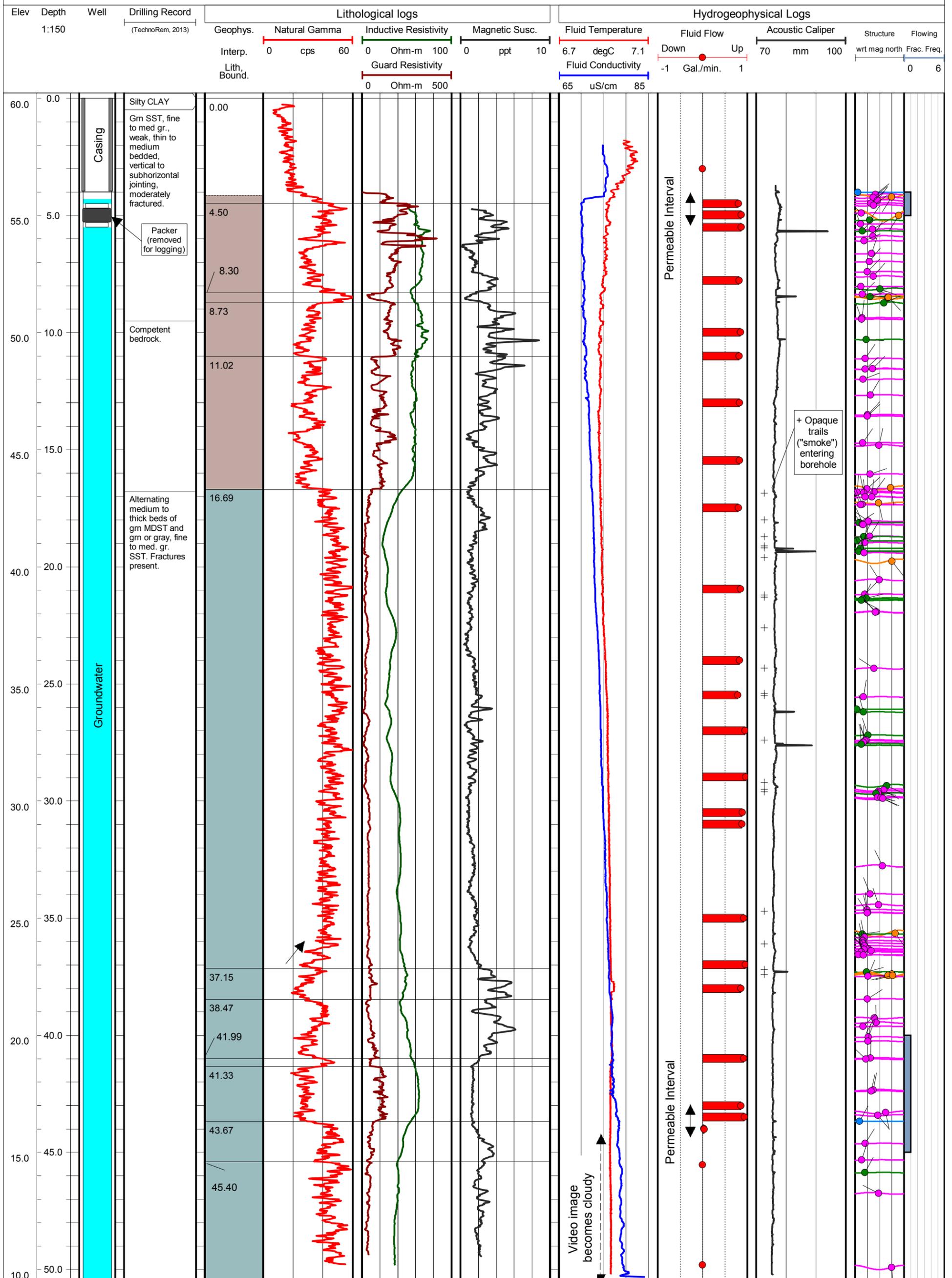


Borehole: POH-11-03  
 Location: Haldimand, QC  
 Project: Grndwater Asmt  
 Study Area: Gaspésie, QC

Easting: 394 098 m  
 Northing: 5 408 227 m  
 UTM Zone: 20  
 Datum: NAD83

Date Drilled: 16-Oct-'12  
 Method: Cored  
 Diameter: 76 mm  
 Depth: 50.46 m

Date Logged: 6,7-Nov-'12  
 Water Level: Artesian  
 Logged By: GSC  
 Log Ref: Soil Surface

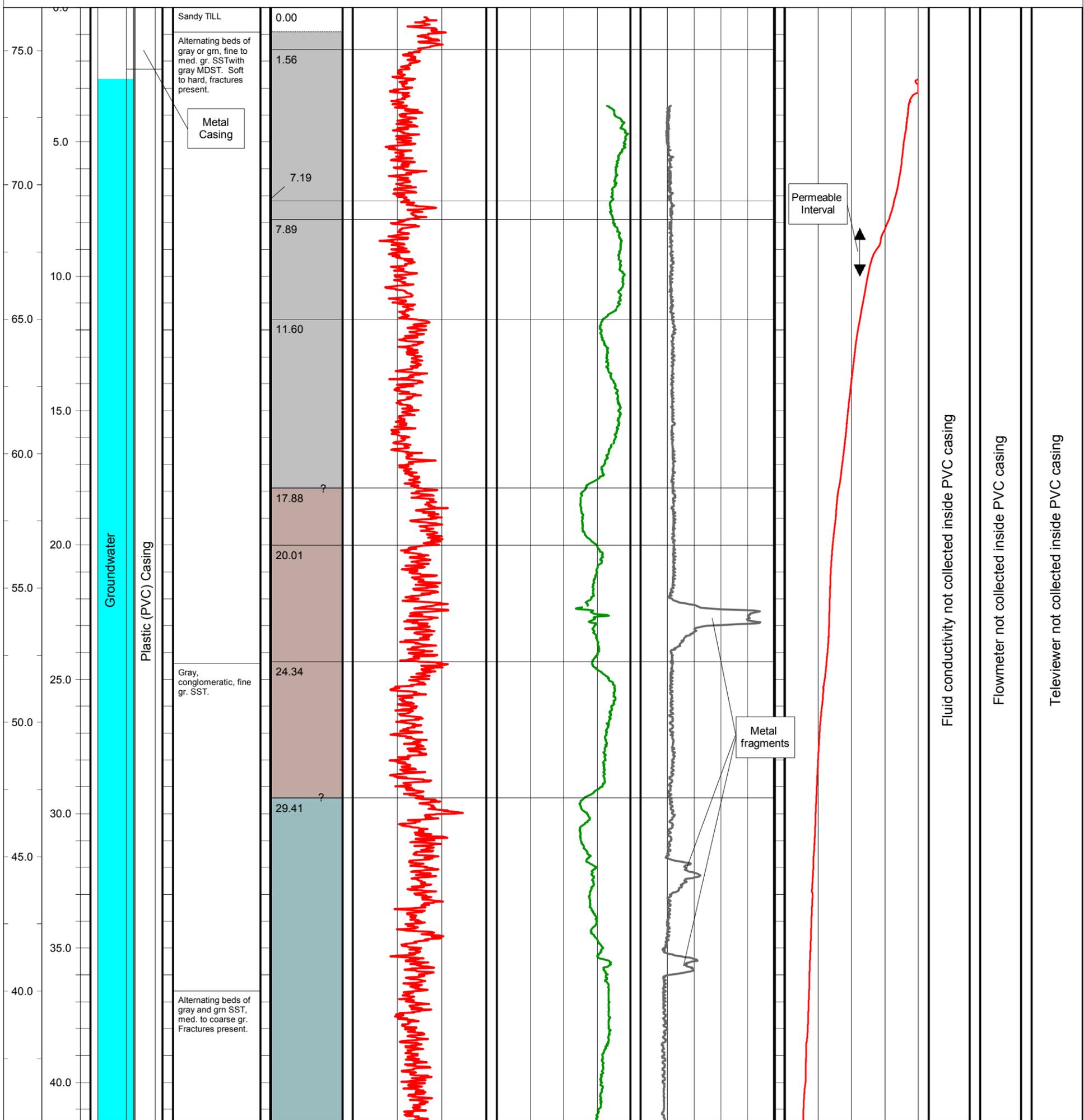
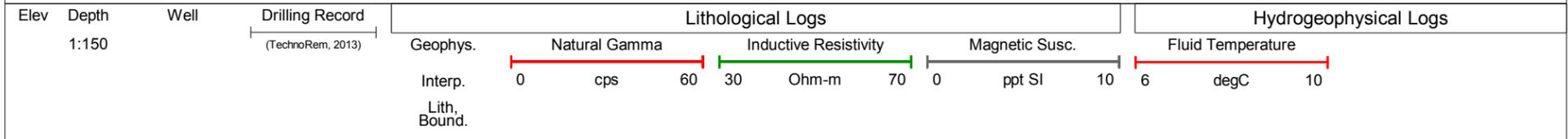


Borehole: POH-11-04  
 Location: Haldimand, QC  
 Project: Grndwater Asmt  
 Study Area: Gaspésie, QC

Easting: 395 965 m  
 Northing: 5 407 683 m  
 UTM Zone: 20  
 Datum: NAD83

Date Drilled: 5-Dec-'11  
 Method: Hammer  
 Diameter: 152 mm  
 Depth: 41.45 m

Date Logged: 12-Nov-'12  
 Water Level: 2.66  
 Logged By: GSC  
 Log Ref: Soil Surface



Fluid conductivity not collected inside PVC casing

Flowmeter not collected inside PVC casing

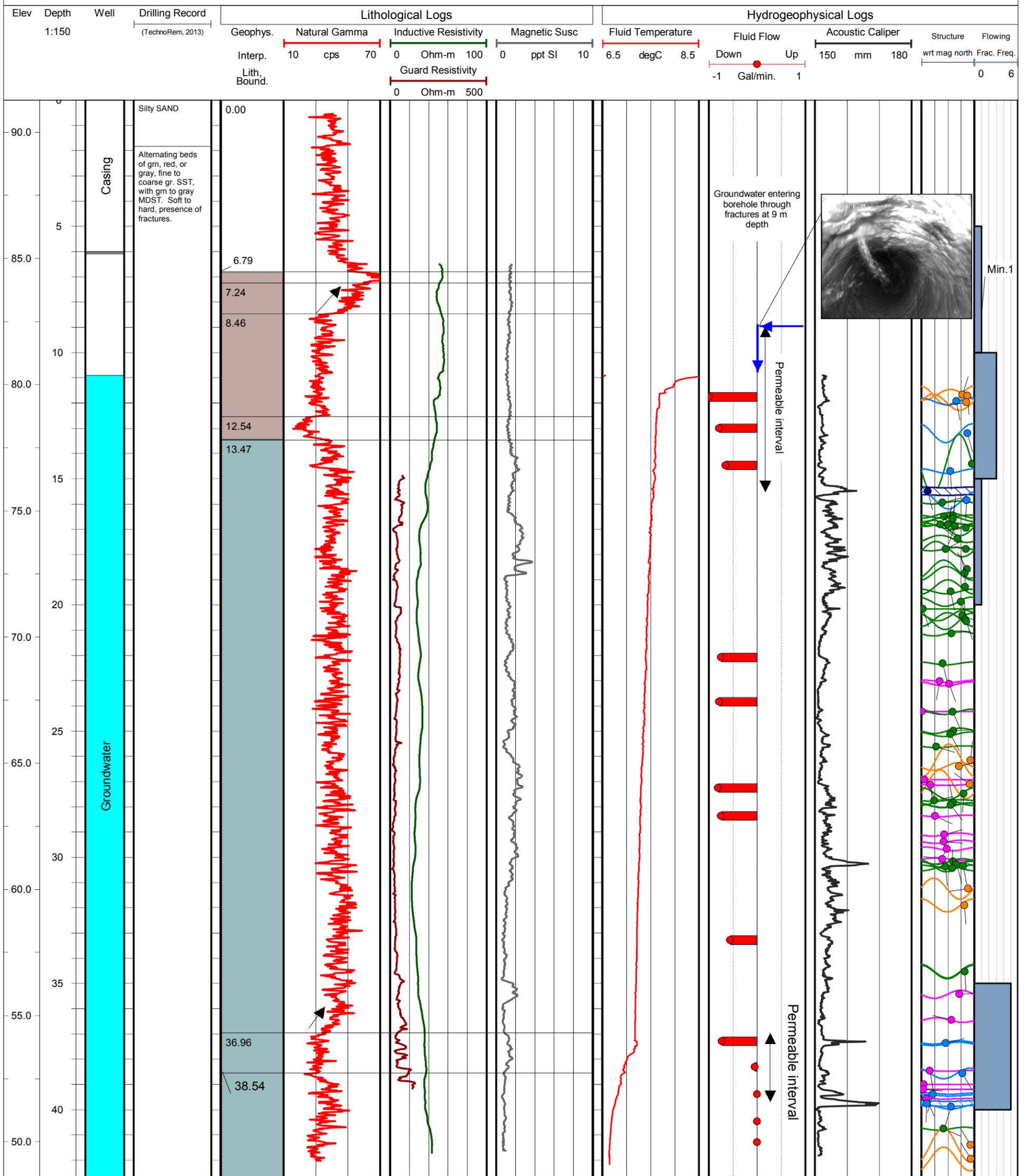
Televiwer not collected inside PVC casing

Borehole: POH-11-05  
 Location: Haldimand, QC  
 Project: Grndwater Asmt  
 Study Area: Gaspésie, QC

Easting: 393 925 m  
 Northing: 5 407 957 m  
 UTM Zone: 20  
 Datum: NAD83

Date Drilled: 3-Oct-'11  
 Method: Hammer  
 Diameter: 152 mm  
 Depth: 42.67 m

Date Logged: 1,2-Nov-'12  
 Water Level: 10.91 m  
 Logged By: GSC  
 Log Ref: Soil Surface

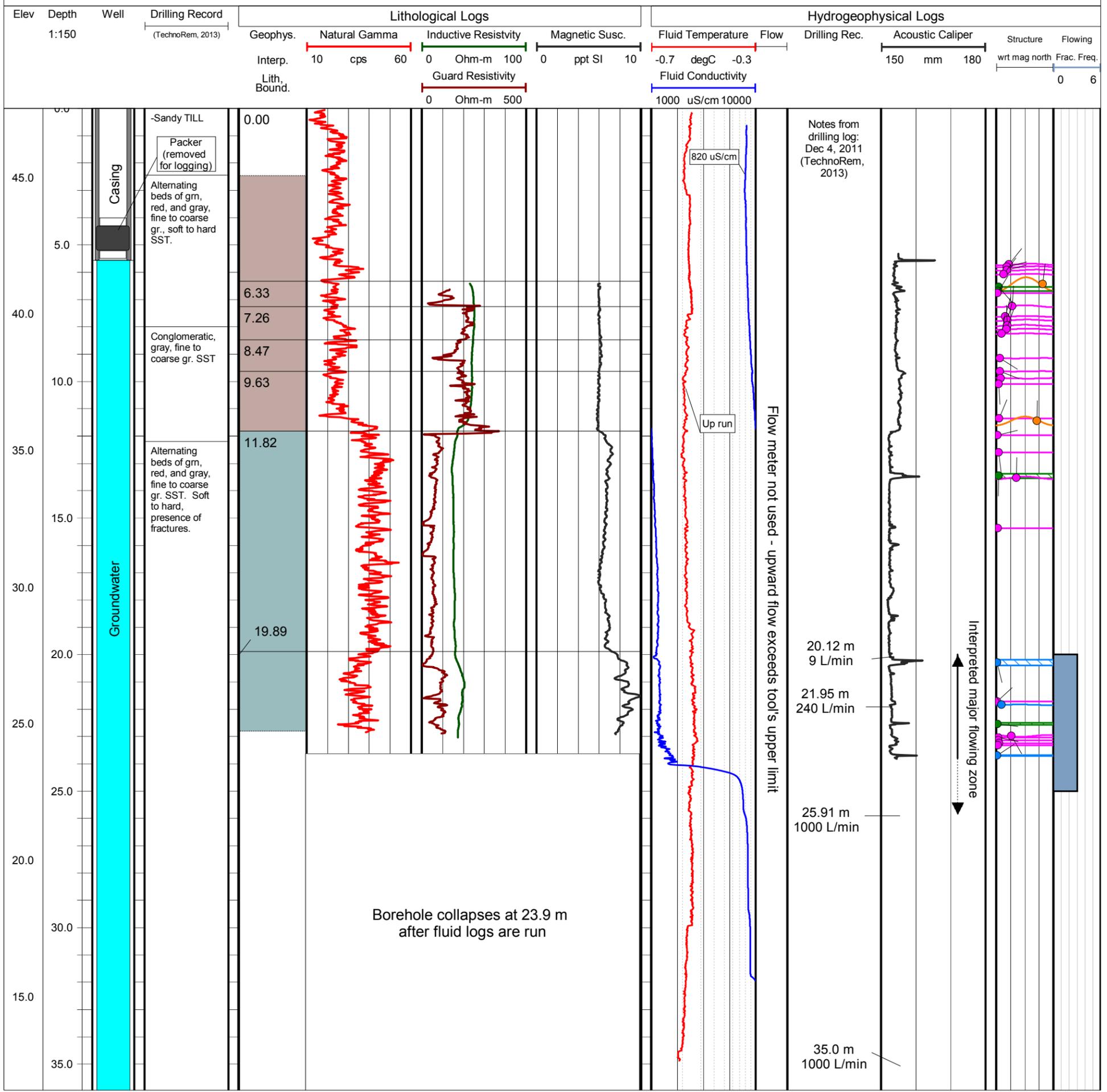


Borehole: POH-11-06  
 Location: Haldimand, QC  
 Project: Grndwater Asmt  
 Study Area: Gaspésie, QC

Easting: 395 903.6 m  
 Northing: 5 406 475.1 m  
 UTM Zone: 20  
 Datum: NAD83

Date Drilled: 4-Dec-'11  
 Method: Perc.-rotary  
 Diameter: 152 mm  
 Depth: 35.96 m

Date Logged: 17,18-Nov-'12  
 Water Level: Artesian  
 Logged By: GSC  
 Log Ref: Soil Surface

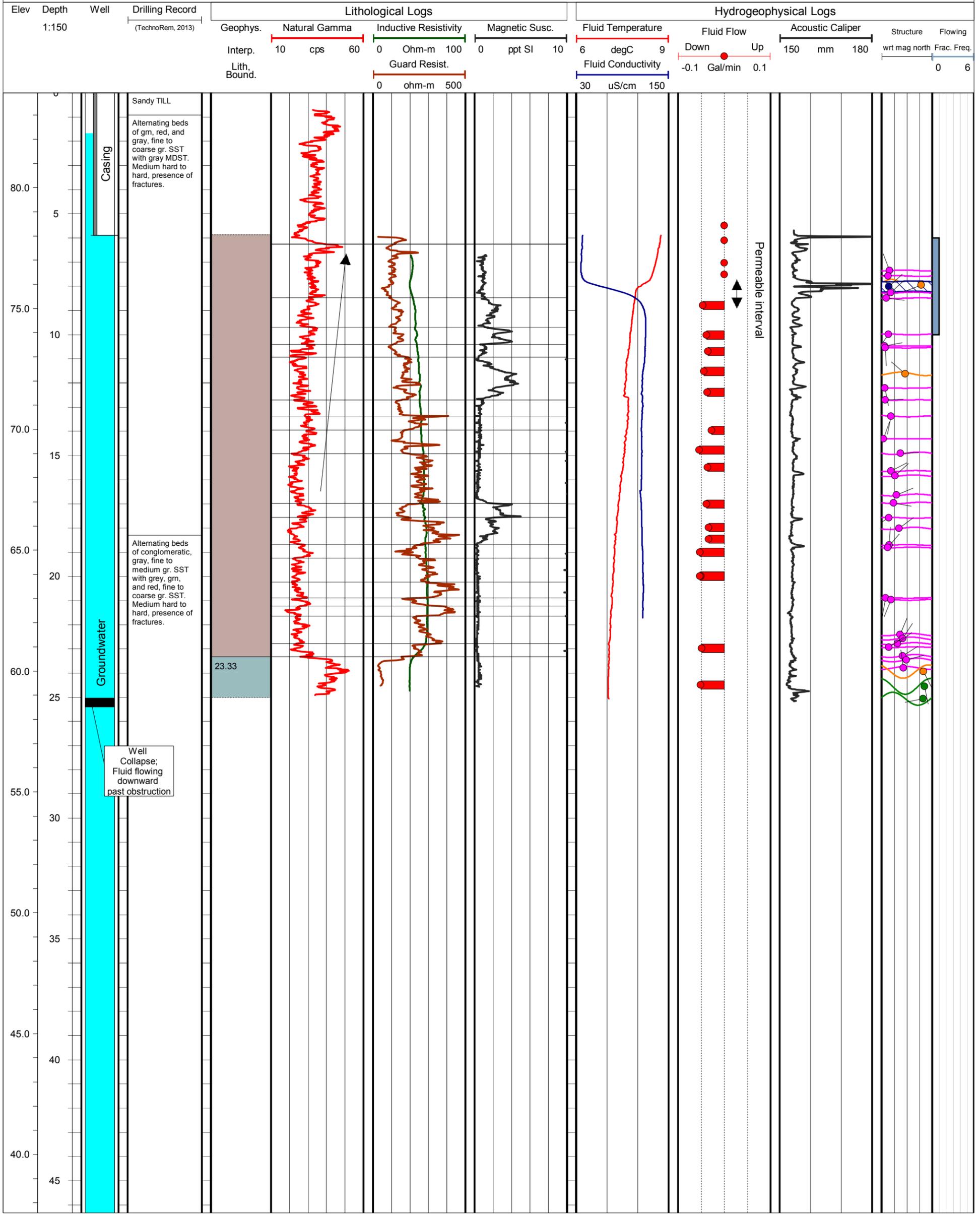


Borehole: POH-11-09  
 Location: Haldimand, QC  
 Project: Grndwater Asmt  
 Study Area: Gaspésie, QC

Easting: 395 574 m  
 Northing: 5 407 156 m  
 UTM Zone: 20  
 Datum: NAD83

Date Drilled: 30-Nov-'11  
 Method: Hammer  
 Diameter: 152 mm  
 Depth: 46.33 m

Date Logged: 5,8-Nov-'12  
 Water Level: 1.67 m  
 Logged By: GSC  
 Log Ref: Soil Surface

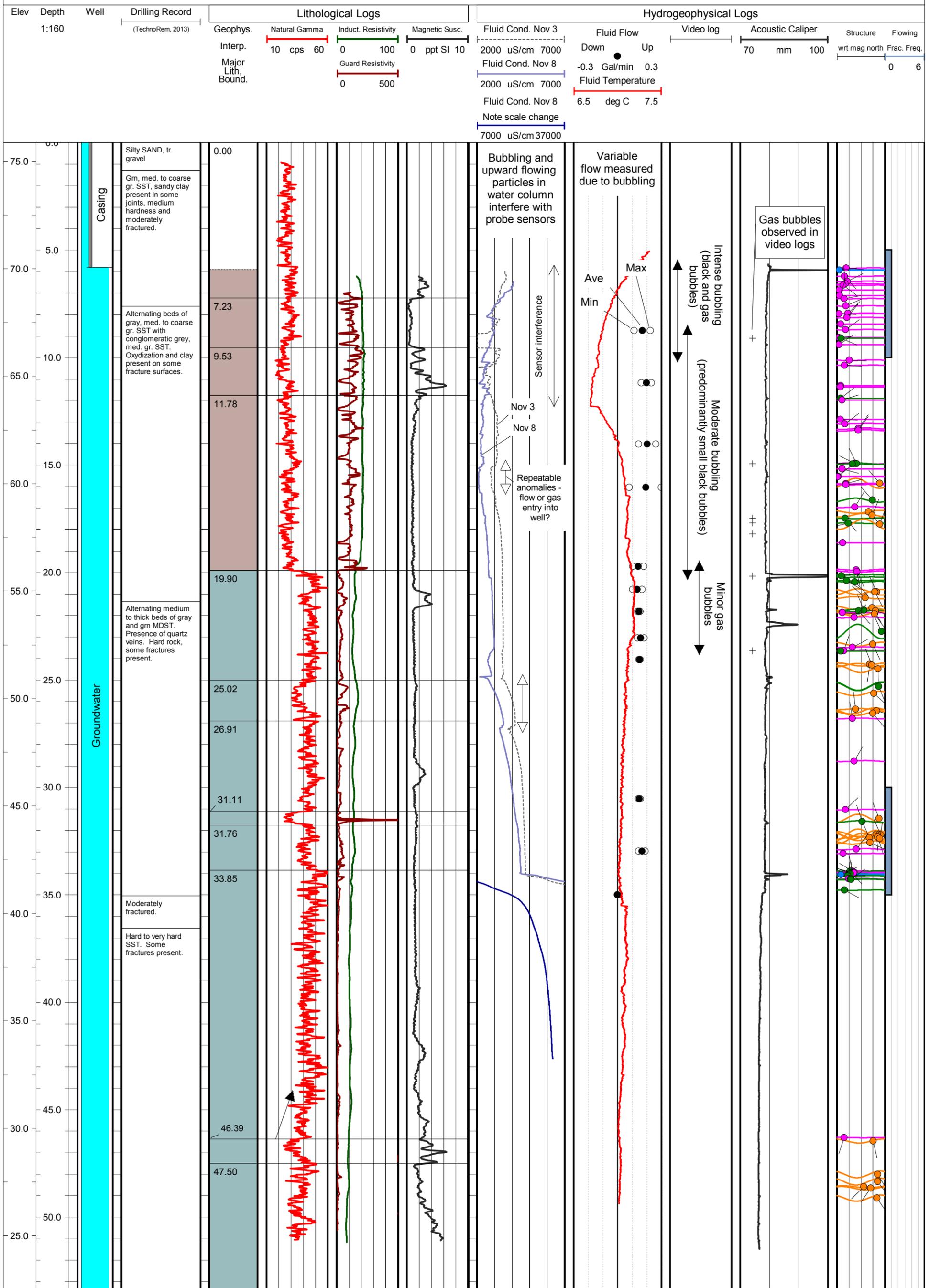


Borehole: POH-11-10  
 Location: Haldimand, QC  
 Project: Grndwater Asmt  
 Study Area: Gaspésie, QC

Easting: 395 575.3 m  
 Northing: 5 407 619.6 m  
 UTM Zone: 20  
 Datum: NAD83

Date Drilled: 2012  
 Method: Cored  
 Diameter: 76 mm  
 Depth: 53.34 m

Date Logged: 3,4-Nov-'12  
 Water Level: 0.02 m  
 Logged By: GSC  
 Log Ref: Soil Surface

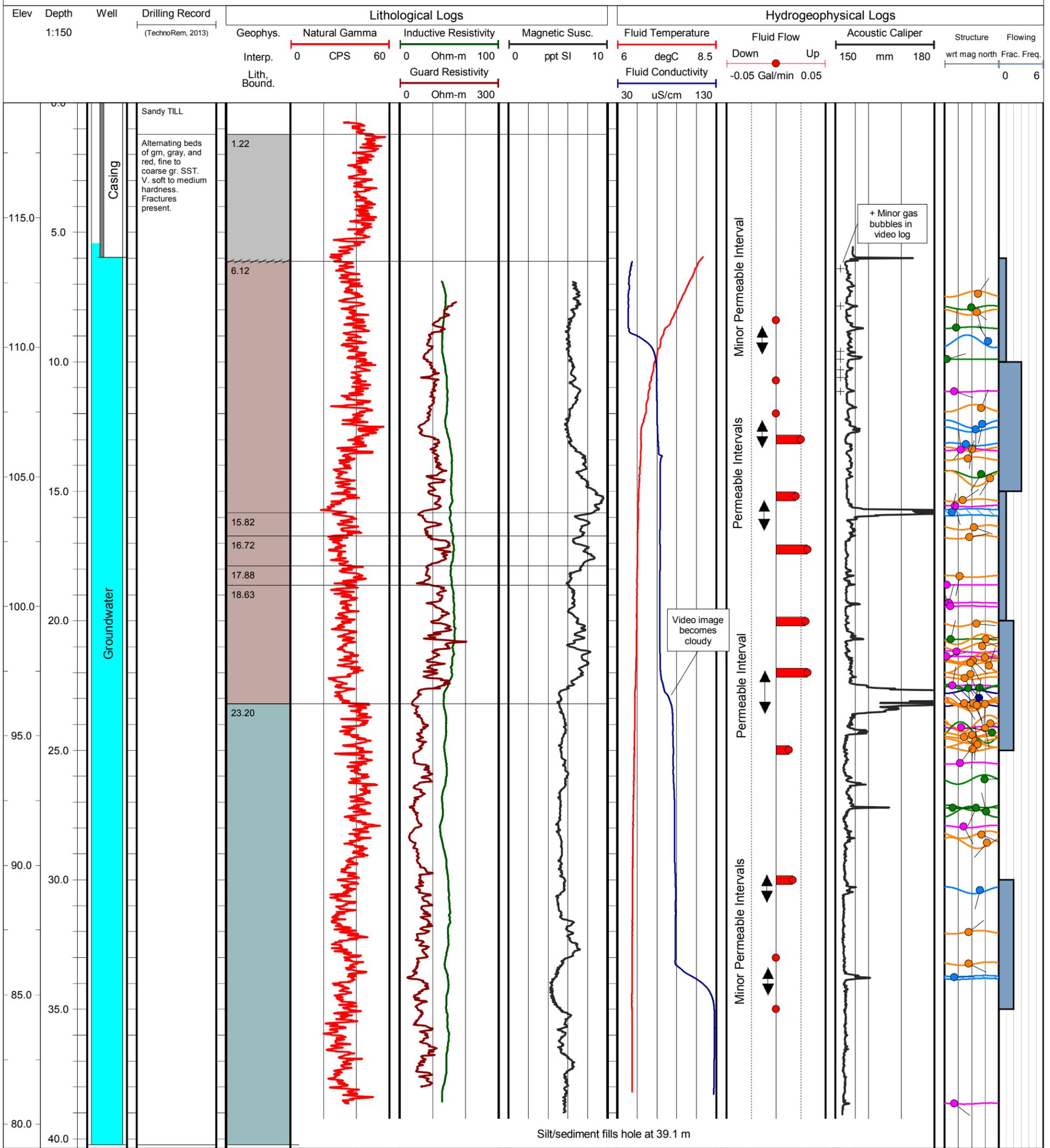


Borehole: POH-11-12  
 Location: Haldimand, QC  
 Project: Grndwater Asmt  
 Study Area: Gaspésie, QC

Easting: 394 629 m  
 Northing: 5 406 859 m  
 UTM Zone: 20  
 Datum: NAD83

Date Drilled: 29-Nov-'11  
 Method: Hammer  
 Diameter: 152 mm  
 Depth: 40.23 m

Date Logged: 15-17-Nov-'12  
 Water Level: 5.42 m  
 Logged By: GSC  
 Log Ref: Soil Surface

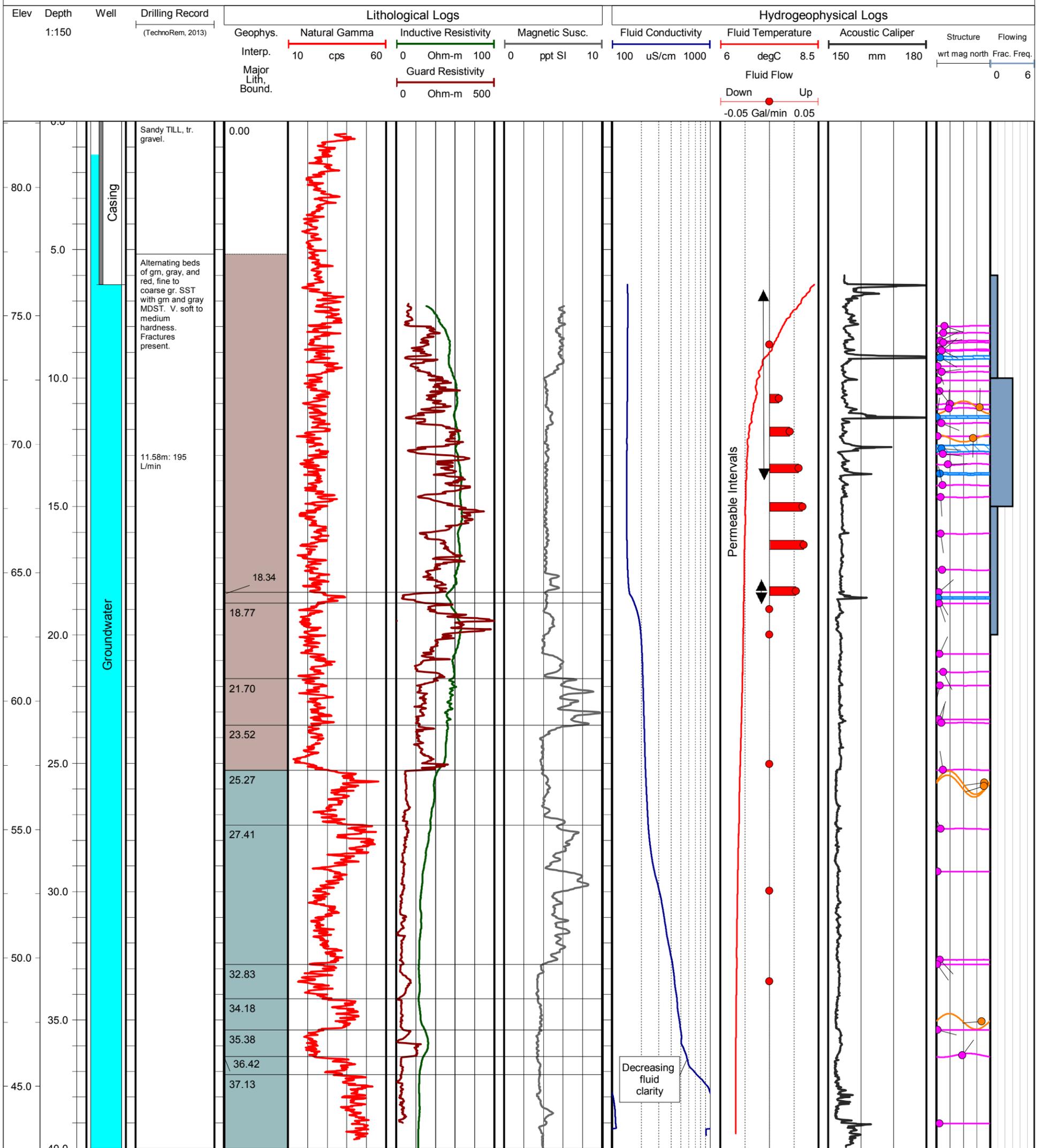


Borehole: POH-11-14  
 Location: Haldimand, QC  
 Project: Grndwater Asmt  
 Study Area: Gaspésie, QC

Easting: 394 727 m  
 Northing: 5 407 765 m  
 UTM Zone: 20  
 Datum: NAD83

Date Drilled: 29-Nov-'11  
 Method: Hammer  
 Diameter: 152 mm  
 Depth: 40.0 m

Date Logged: 13,14-Nov-'12  
 Water Level: 1.29 m  
 Logged By: GSC  
 Log Ref: Soil Surface

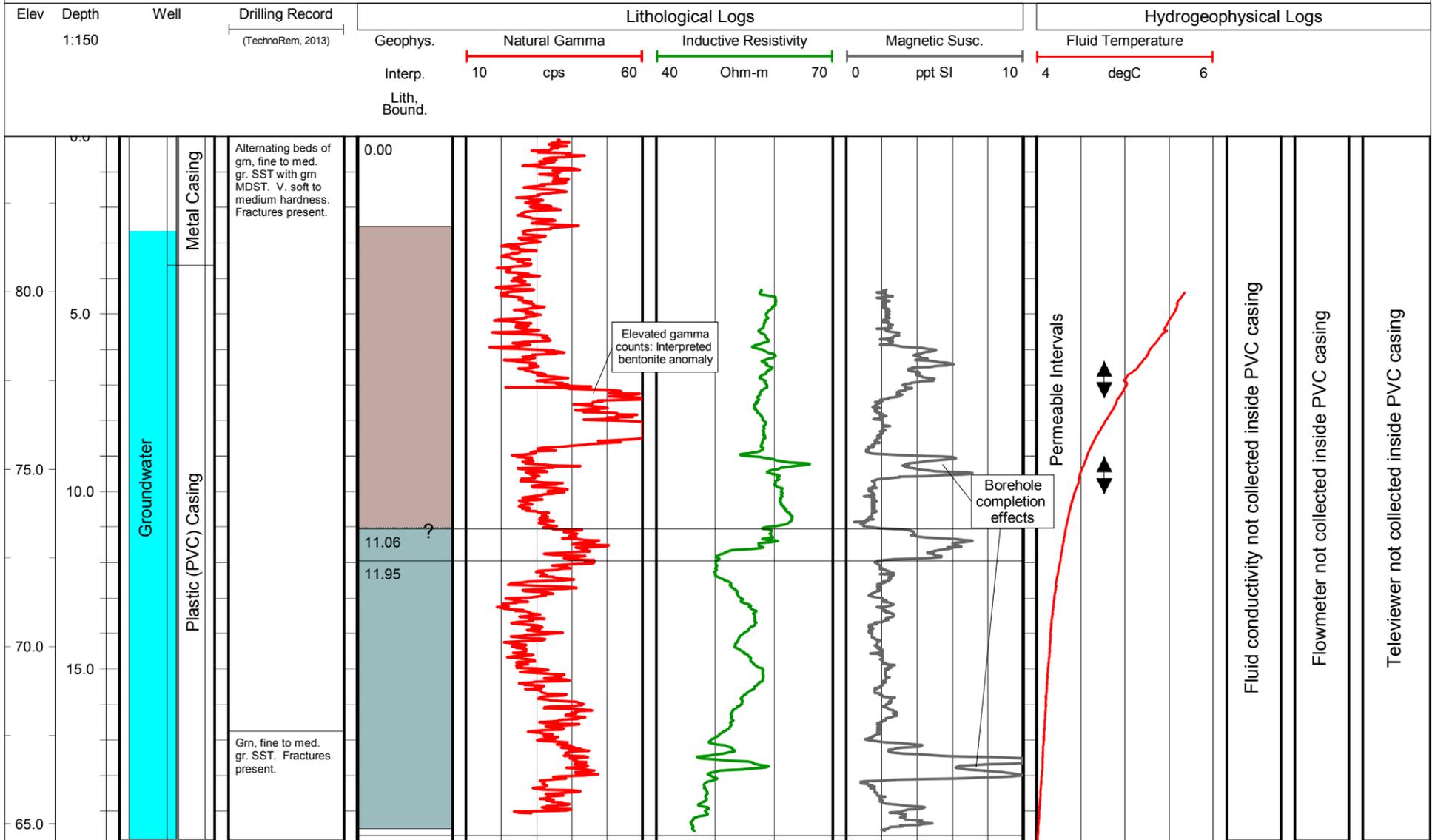


Borehole: POH-11-15  
 Location: Haldimand, QC  
 Project: Grndwater Asmt  
 Study Area: Gaspésie, QC

Easting: 393 947 m  
 Northing: 5 407 643 m  
 UTM Zone: 20  
 Datum: NAD83

Date Drilled: 2011  
 Method: Hammer  
 Diameter: 152 mm  
 Depth: 19.80 m

Date Logged: 10-Nov-'12  
 Water Level: 3.63  
 Logged By: GSC  
 Log Ref: Soil Surface



## APPENDIX II

### Geophysical Log Background

Appendix II provides background information on the downhole logging methods used in this project. The tools described in the logging suite are Mount Sopris logging tools, except for the fluid temperature and conductivity which were developed in-house.

#### 1.0 Gamma Methods

**Natural gamma logging** detects the presence of naturally occurring or man-made radioactive isotopes. The most common naturally-occurring isotopes in rock and soil are potassium (K), uranium (U), and thorium (Th), the most common being potassium in rock forming minerals.

Natural gamma logging tools measure radioactivity by converting gamma rays (photons) emitted from the formation into electronic pulses using a scintillator crystal (detector) in the tool. For total count gamma logging, it is sufficient to count the total number of pulses per second. In spectral gamma logging, the amplitude of the pulse is needed to determine whether the gamma ray energy lies within the range corresponding to the windows for K, U, or Th. At each depth interval, a spectrum (counts per second versus energy levels) is built from the amplitudes of the incident gamma particles (Figure III-a). The counts from each window can be later processed to calculate the weight percent of K, U, and Th in the formation using curves determined at downhole calibration facilities.

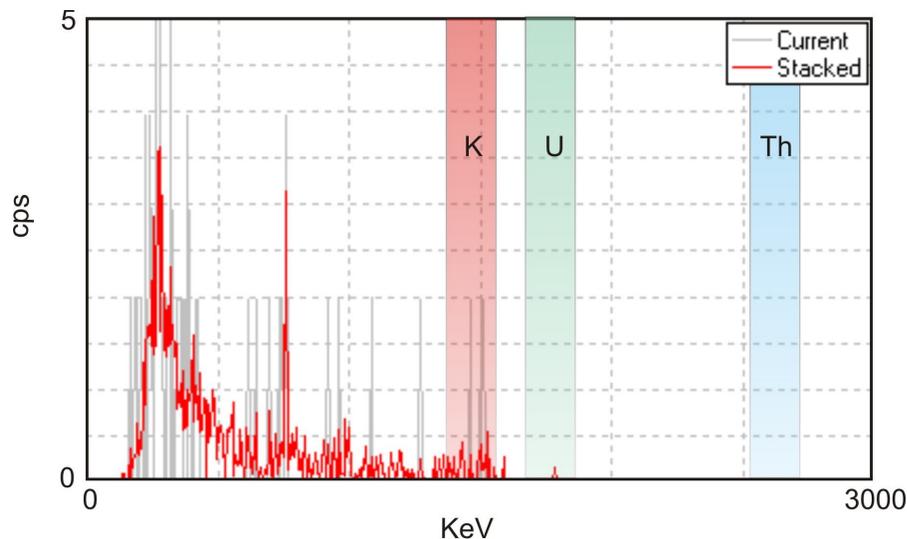


Figure III-a. Sample spectrum indicating counts within the potassium (K), uranium (U), and thorium (Th) windows.

Radioactive decay is statistical in nature and photon emission follows a Poisson's distribution. The standard deviation of the count number will be its square root. The accuracy of the measurement is greatest at high count rates over slower logging speeds. Therefore it is preferable to maintain a very low logging speed.

When overburden units are logged, relative abundances of potassium, and especially uranium and thorium will generally be low, if present. This is particularly true in finer grained soils where the heavier elements were dropped out of suspension earlier in the sedimentary process, although

exceptions exist. In soils, therefore, gamma energy is generally more present in the lower ranges due to scattering, and can be used as a relative indicator of grain size. A denser formation will cause the natural radiation to be attenuated more quickly, therefore coarser grain sizes will tend to have a lower count rate, while softer soils with finer grain sizes (silt/clay) and higher porosity will tend to record higher count levels.

## **2.0 Electromagnetic Induction Methods**

The **apparent conductivity** logging tool uses an alternating current of 40 kHz AC in a dipole transmitter to generate a magnetic field which induces electric fields in the formation. A dipole receiver in turn measures the responding signal, whose quadrature phase is proportional to the conductivity of the materials intersected by the borehole. Additional coils are used to focus the current out into the borehole to reduce the tool's sensitivity to the borehole fluid and improve its vertical resolution.

In soil and rock logging, the apparent conductivity measured is a bulk conductivity, meaning that the grains and pore water both contribute to the total conductivity values. If the pore water is saline or otherwise conductive (e.g. leachate contamination), this will overwhelm the conductivity of the soil/rock matrix. In absence of conductive pore water, the conductivity tool provides a method of identifying variation in stratigraphic units, and tends to mirror the trends of the natural gamma log, where fine-grained materials tend to be more conductive than coarse.

The **magnetic susceptibility** measurement is the ratio between the primary magnetic field and the in-phase component of the magnetic field produced by the host material. Although traditionally used for downhole mineral exploration due to its sensitivity to magnetic minerals (e.g. magnetite, ilmenite, pyrrhotite), the susceptibility tool has been shown to be extremely useful for lithological logging purposes in unconsolidated sediments and sedimentary rocks of low susceptibilities (McNeill et al., 1996).

Although these inductive tools are quite similar, lithological mapping requires a very sensitive magnetic susceptibility logger (in the sub-parts-per-thousand SI) with a high degree of temperature compensation. Therefore, two induction tools are used for the conductivity and susceptibility logging, with slightly different coil configurations and temperature compensation electronics.

Note that the unit for magnetic susceptibility is most commonly SI, but some texts also use the unit CGS. The conversion between these two systems is:

$$SI = 4\pi * CGS.$$

## **3.0 Electrical Methods**

The **guard resistivity** log, a type of focused-resistivity measurement, is designed to identify the boundaries of thin beds and measure their resistivity, even in the presence of highly conductive fluids (see Keys, 1997; Hearst, 2000). As opposed to induction methods, the guard tool comes into direct contact with the borehole walls and is run in open boreholes. A button electrode on the side of the tool emits a small AC current (50  $\mu$ s) into the formation. The tool body forms the guard electrode which maintains a constant potential surface, forcing the current out into the rocks surrounding the well and diminishing any current flow along the wellbore. The result is a focused resistivity measurement with

a vertical resolution of approximately 2.5 cm (Mount Sopris, 2009). This tool provides **qualitative resistivity values**, not a true resistivity measurement.

## **4.0 Fluid Logging Methods**

### **4.1 Fluid Temperature**

The GSC conducted borehole research in the late 70's and early 80's on techniques for high resolution temperature measurements on the order of 0.0001°C. The purpose was to investigate the feasibility of recording temperature gradients in fluid-filled boreholes which would reflect the intersected lithology (Bristow and Conway, 1984). The GSC has recently redeveloped a temperature tool based on the original GSC design which could also potentially identify small temperature changes indicative of fluid movement behind casing for groundwater studies, as well as subtle changes in temperature in open rock holes where fluid is entering or exiting the borehole through flowing fractures.

To be effective, the temperature tool must be the first probe to enter the borehole after the fluid has been able to stabilize for at least 24 hours, and the log must be recorded in the downward direction. Slow logging speeds prevent mixing of the fluid ahead of the probe and allow time for the thermistor to react to slight changes in temperature. Gradient calculations ( $dT/dz$ ) assist in identifying zones where fluctuations occur over very small changes in temperature.

### **4.2 Fluid Conductivity**

The GSC's fluid conductivity tool is similar in design to the temperature tool, but uses two electrodes in the base (bullnose) of the tool to measure changes in fluid conductivity. The tool's response is calibrated in the lab against four calibration solutions of varying conductivity (deionized water ~0  $\mu\text{S/cm}$ , 178  $\mu\text{S/cm}$ , 1460  $\mu\text{S/cm}$ , and 12880  $\mu\text{S/cm}$ ).

As with the temperature tool, the conductivity tool must be among the first probes to enter the borehole after the fluid has been able to stabilize for at least 24 hours, and the log must be recorded in the downward direction. Slow logging speeds prevent mixing of the fluid ahead of the probe and allow time for the electrodes to react to slight changes in fluid conductivity.

### **4.3 Heat Pulse Flow meter**

Many methods have been developed over recent decades to measure vertical fluid flow along an open borehole or well screen for groundwater applications. These methods have included impellers, tracer-release methods, thermal-pulse flow meters, and electromagnetic (EM) flow meters. Thermal and EM vertical component flow meters are quite sensitive in low-flow conditions, permitting high-resolution measurement of the ambient vertical flow in natural or pumped borehole environments. Ambient flow measurements provide information on the direction of the vertical component of the hydraulic gradient and the location of hydraulically active features in fractured bedrock. Measurements made under pumped conditions provide information on the relative differences in the permeability of targeted bedrock zones or fractures.

The heat pulse flow meter used in these surveys (HFM-2293 manufactured by Mount Sopris Instrument Co.) is based on a design by the US Geological Survey to collect measurements in low-velocity flow environments (Hess, 1982, 1986). This flow meter contains a heating grid with

equidistant temperature sensors positioned a few centimetres above and below the grid. Rubber diverter petals centralize and seal the probe in the borehole, forcing the fluid to pass through a wire mesh over the heating grid and the sensors. When the tool is in position for a series of readings, a heat pulse is triggered by the user on a laptop computer. The grid heats a lens of water that moves up or down with the flow of the borehole fluid past either the upper or lower sensor. An amplifier detects the difference in temperature between the sensors, and converts the output to a frequency which is sent up the cable and recorded by the laptop. The software records the time elapsed between when the heat pulse was triggered and when the sensor records the peak temperature change, carried by the flow.

If natural flow is not detectable in the borehole (i.e.  $<0.110$  l/min), artificial upward flow can be induced with a submersible pump to determine the relative flow drawn from permeable fractures. Flow rate must be carefully monitored every few minutes on surface using a graded container and a stopwatch, while water levels are measured in the borehole using a water level meter. This ensures the change in flow rate measured by the tool can be attributed to changes in hydraulic conductivity of the rock mass and not to changes in the pumping rate. The pump's flow rate must be carefully adjusted so it does not exceed the tool's upper limit of 3.78 l/min, and also to equalize the pumping rate with the recharge (i.e. no measurable drop in water level during the pumping). In non-hydraulically conductive boreholes, reaching stability is very difficult, and sometimes not possible. In these cases, the flow results are converted from a volumetric value, to a percentage of the total pumping rate measured simultaneously at the surface during the downhole flow measurement.

Flow meter measurements are influenced by number of factors, including the construction and degree of development of a well, and the natural hydrogeological conditions: factors which can change over time. Logging conditions during the test will also influence the results. Proper sealing with the tool's rubber diverters is critical, as a poor seal caused by borehole wall enlargements (such as in fractures or washouts) will influence flow determinations. Collecting caliper and fluid temperature/fluid conductivity logs before flow meter logging guides the selection of test intervals. Allowing sufficient time for the fluid to settle after moving the tool in the borehole is also critical, particularly in wells with very low ambient flows.

## **5.0 Imaging Methods**

Televiwers collect images of the inside of the borehole wall in very high resolution, either using ultrasonic pulses (acoustic televiewer, ATV), or color digital scans (optical televiewer, OTV). The tools are highly effective in the detection and evaluation of fractures, lithological characterization, dip and dip direction of features for rock mass structural analyses, and casing inspections.

### **5.1 Acoustic Televiewer (ATV)**

The **ATV** transmits a pulse from a fixed transducer and a rotating focusing mirror, and records the amplitude and travel time of the signal reflected by the borehole wall. The ATV used in these surveys (the ABI40, manufactured by Advanced Logic Technology SA.) records the entire reflected wave train, and processing algorithms allow the software in real time to determine the first reflection from the tool's acoustic window, the bedrock wall, and all other subsequent reflections.

Line scans of the borehole wall are collected in intervals as small as 1 mm, and at a resolution as high as 288 pixels/revolution. The number of pixels per degree will depend on the diameter of the borehole. To collect images this detailed, the tool must be run very slowly ( $\sim 1$  m/min) however a slight decrease

in quality (i.e. 2 mm intervals and/or fewer pixels/rev) can allow for a faster logging speed (~2-3 m/min).

The tool is equipped with an APS544 orientation sensor, containing a 3-axis magnetometer and 3 accelerometers, to constantly resolve magnetic north and the tilt of the tool. Each line scan contains the direction of magnetic north, and also the tilt of the borehole at that depth. The tool can resolve azimuth with an accuracy of 1°, and tilt to an accuracy of 0.5°. When the travel time and amplitude images are imported into processing software, they can be oriented to magnetic north (or to the high side of the borehole in the case of inclined borings). Once the dip and dip direction of structural features are interpreted, they can be corrected for any tilt of the borehole from vertical.

Centralization is key in the collection of high quality images, particularly with the ATV. The tool is kept centered in the borehole with the use of two or more bowspring arm centralizers, made of non-magnetic material, fixed to the tool's housing.

The ATV's travel time image can be processed to build a 360° caliper of the borehole shape. This can then serve as a mesh around which the amplitude image can be draped to create a 3D image of the borehole. Features such as open fractures and washouts can be better visualized using this technique.

## **References**

- Bristow, Q., and Conaway, J.G., 1984. Temperature Gradient measurements in boreholes using low noise high resolution digital techniques, Current Research, Part B, Geological Survey of Canada, Paper 84-1B, p.101-108.
- Hearst, J.R., Nelson, P.H. and Paillet, F.L., 2000. Well Logging for Physical Properties; John Wiley and Sons Ltd., England, 483 p.
- Hess, A. E., 1982. A heat-pulse flowmeter for measuring low velocities in boreholes, U.S. Geological Survey Open-File Report 82-699, U.S. Geological Survey, Reston, Virginia.
- Hess, A. E., 1986. Identifying hydraulically conductive fractures with a slow-velocity borehole flowmeter, Canadian Geotechnical Journal, 23:69-78.
- Keys, W.S., 1997. A practical guide to borehole geophysics in environmental investigations; CRC Press Inc., Boca Raton, FL., 176 p.
- McNeill, J.D., Hunter, J.A., and Bosnar, M., 1996. Application of a borehole induction susceptibility logger to shallow lithological mapping, Journal of Environmental and Engineering Geophysics, Vol. 1, p. 77-90.
- Mount Sopris Instruments, 2009. 2GDA-1000 DX Series Dual Density/Guard/Caliper Probe Manual, Mount Sopris Instruments Co. Inc., Golden Colorado, rev. August 7, 2009.

## APPENDIX III

Digital data:

- LAS digital log files
- Excel spreadsheets of flow meter tests
- Structural dataset