Geophysical Logging for Characterization of Bedrock Geothermal Boreholes

Introduction: John Rhyner / *Egg Geo, LLC*

Speaker: John Williams / *USGS*

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Geophysical Logging for Characterization of Bedrock Geothermal Bores

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U.S. Department of the Interior
U.S. Geological Survey

Objectives

- Provide an overview of geophysical logging tools and methods applicable to the characterization of geothermal bores in bedrock
- Present examples of geophysical log analysis and resulting information in multiple hydrogeologic settings

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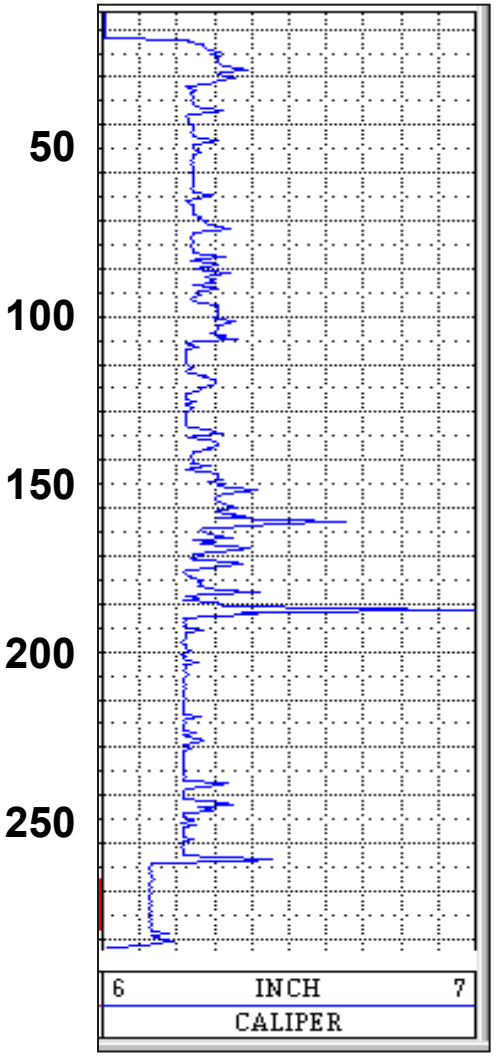
Williams and Paillet (2023)

Caliper Log

- Measures borehole diameter
- Delineates enlargements of borehole diameter related to bit changes, washouts, and fractures
- Used for determining borehole volume for grouting
- Used in the interpretation of geophysical logs affected by borehole diameter



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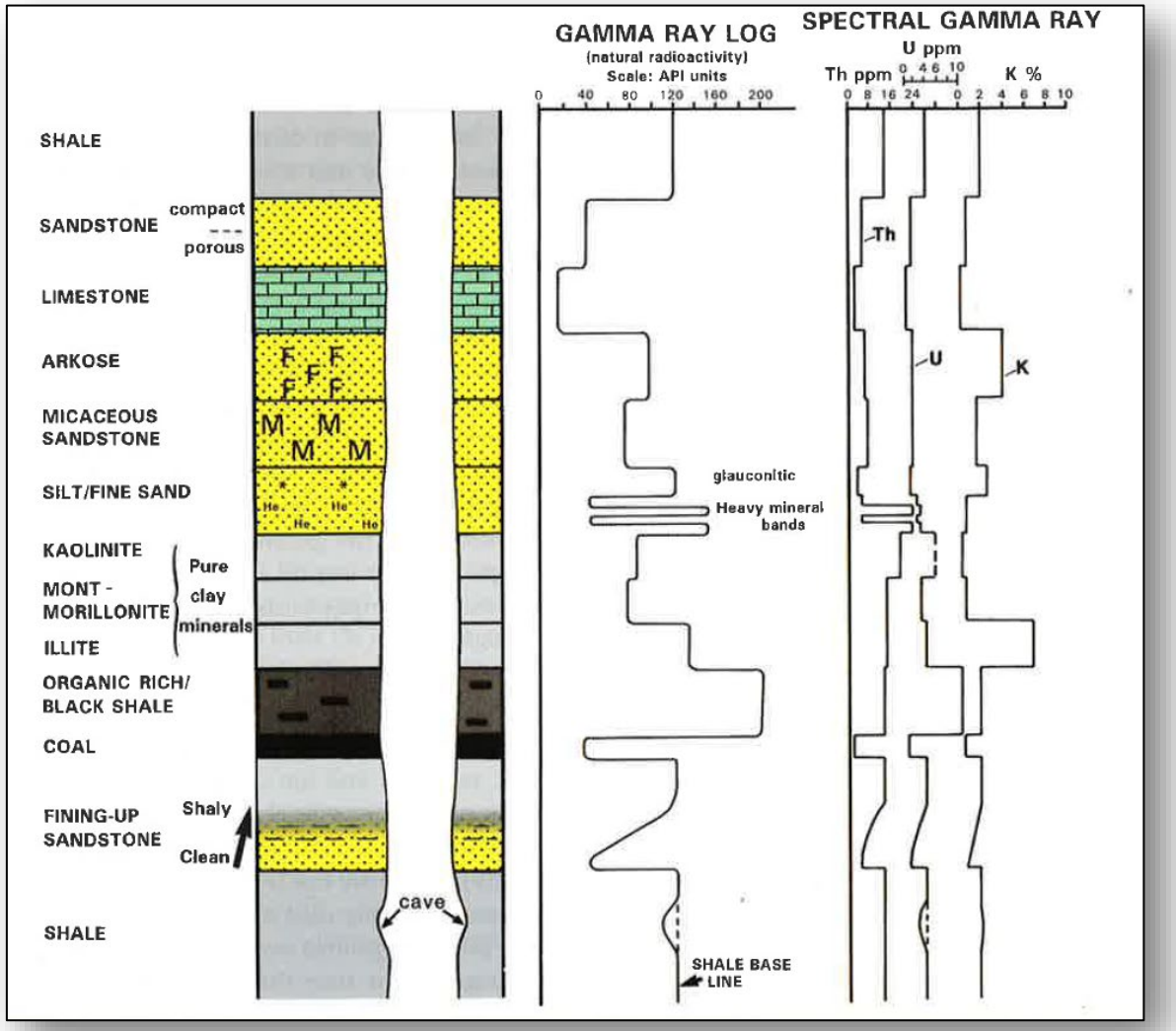
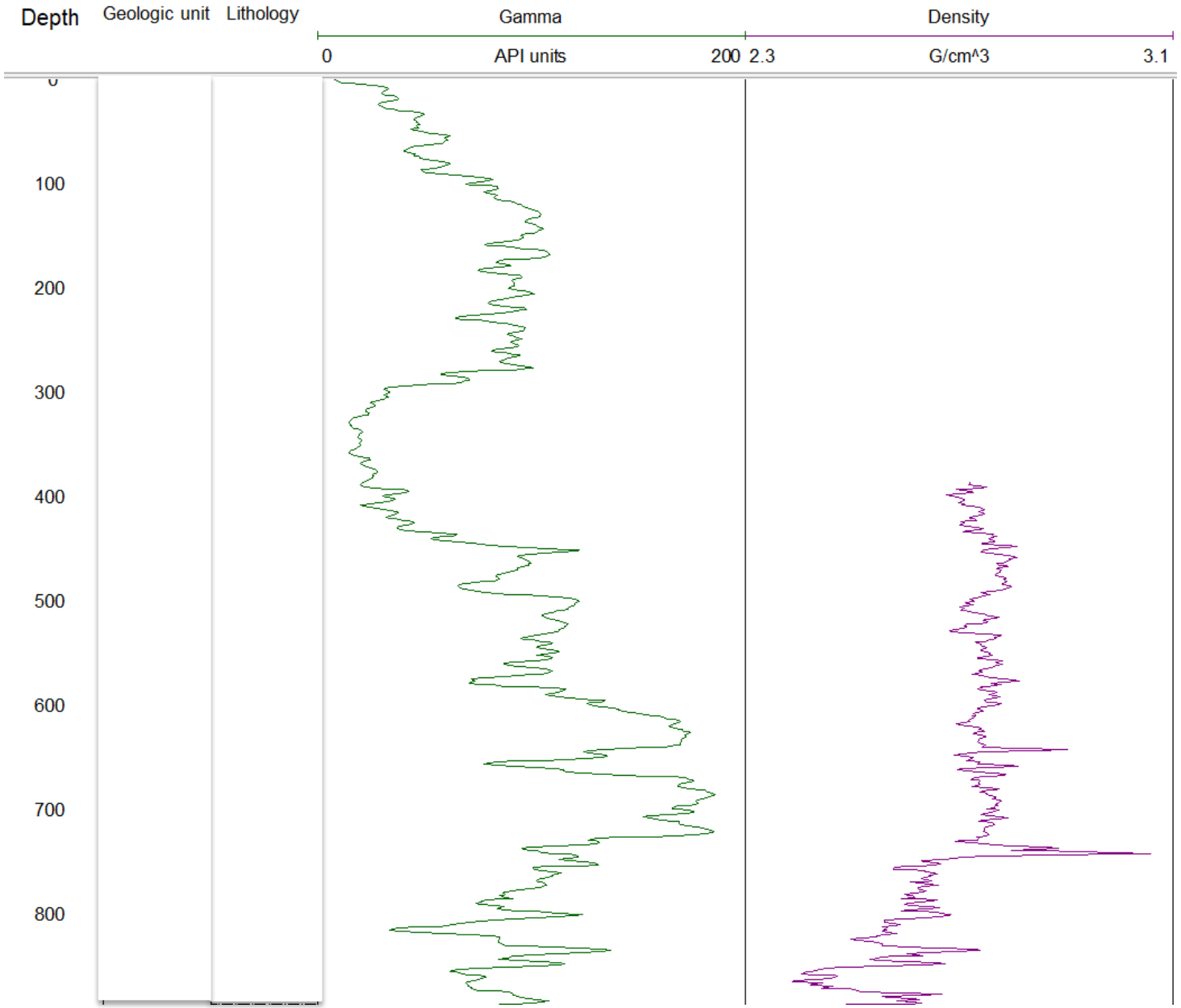
Gamma-Ray Log

- Gamma-ray emissions (cps)
- Uranium, thorium, and daughter products of potassium 40
- Clay content and mineralogy
- Vertical resolution 1 to 2 ft
- Air , water, or mud filled; open, PVC, or steel cased
- Used for lithologic identification



Rider and Kennedy (2011)

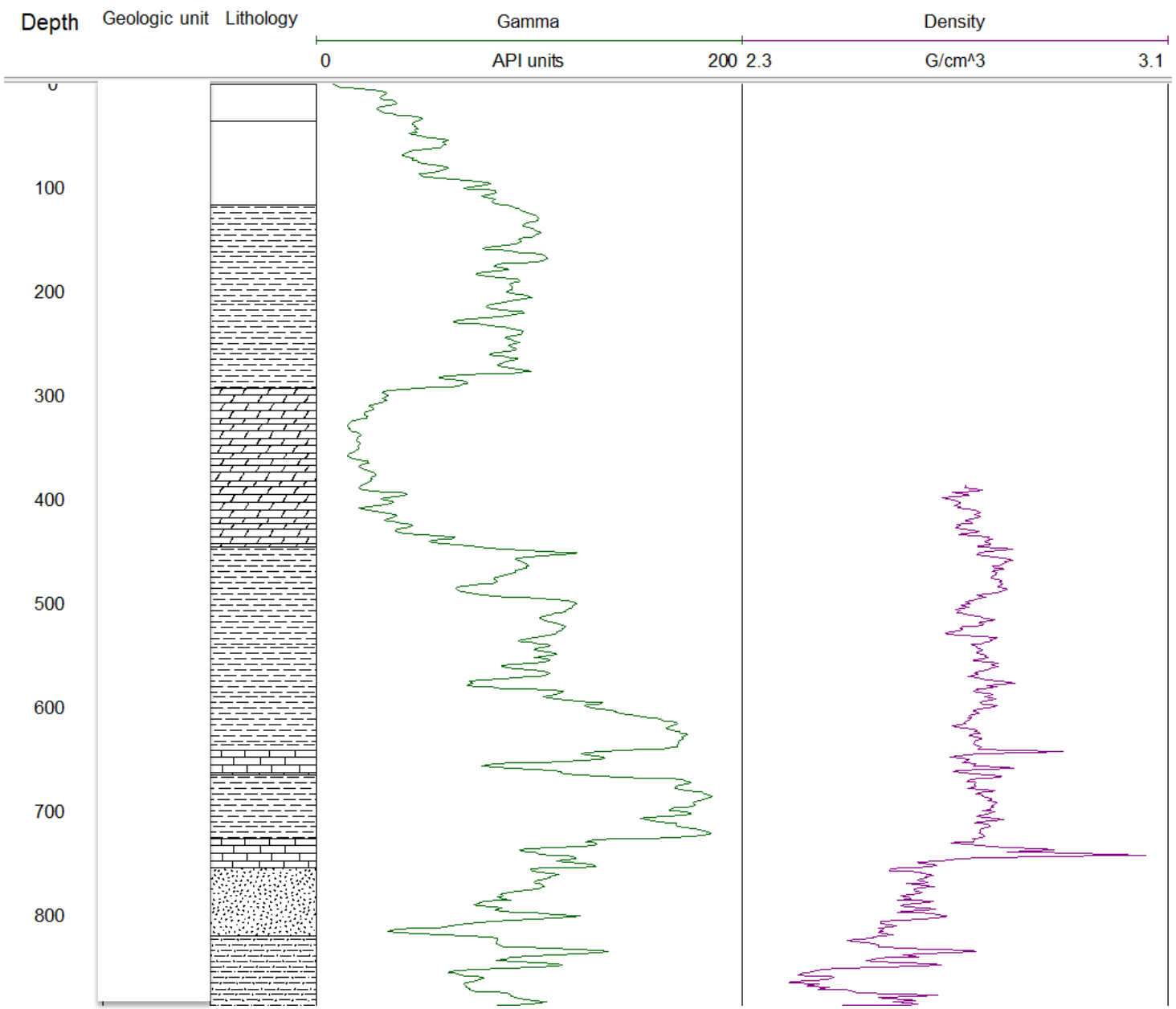
USGS



Gas well in Ontario Lowlands
Silurian shale, limestone, dolomite, and evaporites

NYSM ESOGIS

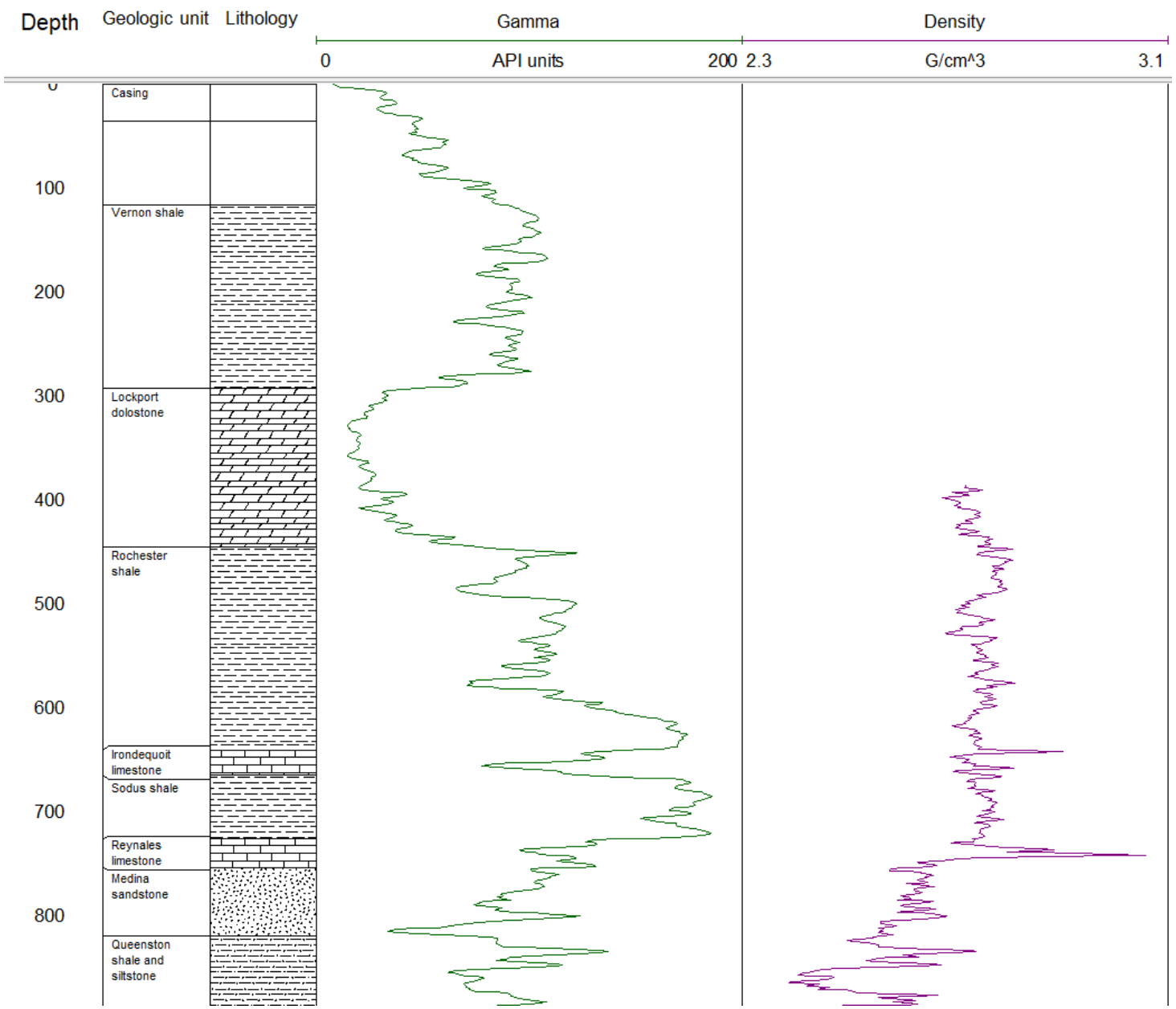
USGS



NYSM ESOGIS

Gas well in Ontario Lowlands
Silurian shale, sandstone, limestone, dolomite, and evaporites

USGS



Gas well in Ontario Lowlands
Silurian shale, limestone, dolomite, and evaporites

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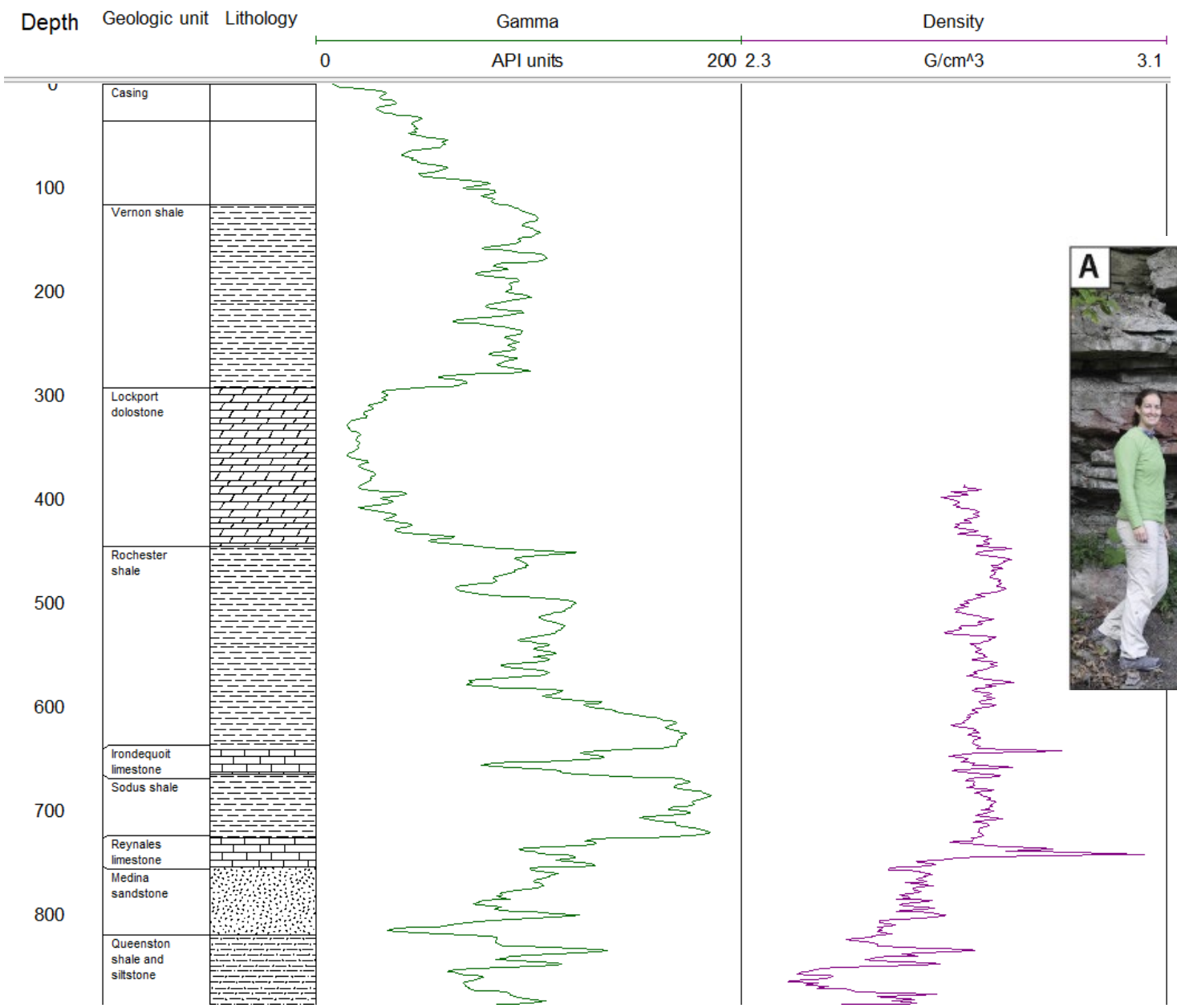
USGS



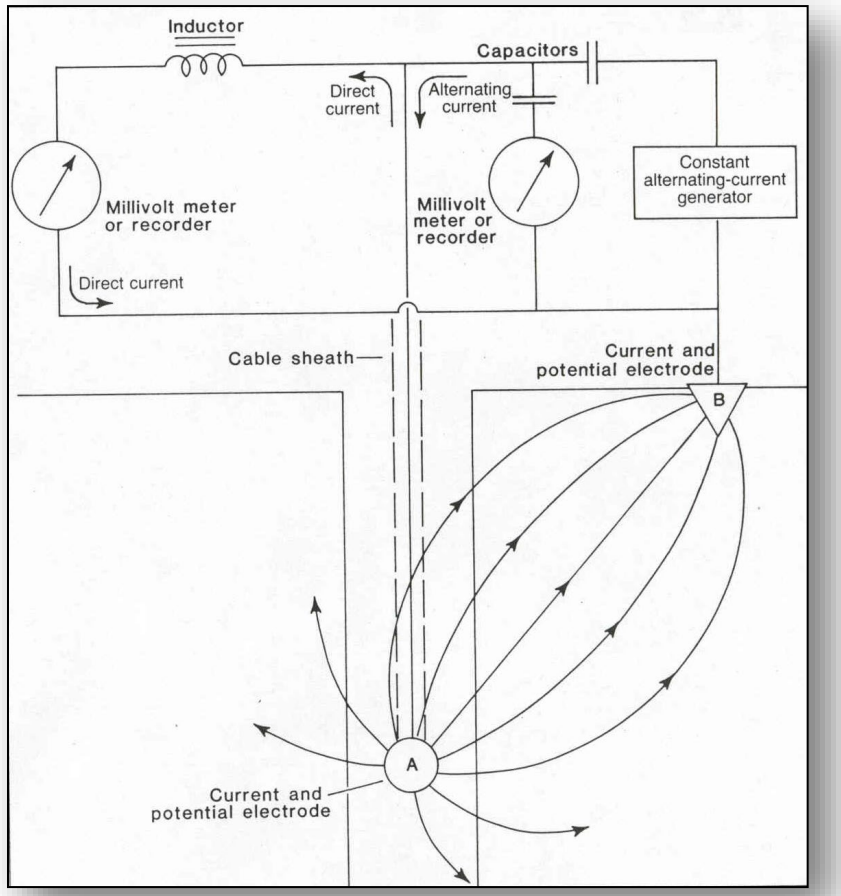
NYSM ESOGIS

Gas well in Ontario Lowlands
Silurian shale, limestone, dolomite, and evaporites

Matheson and Pufahl (2021)

Single-Point Resistance Log

- Electrical resistance between a surface electrode and a downhole electrode
- Clay content, porosity, and dissolved solids
- Resistance(ohms) NOT resistivity(ohms-m)
- Affected by borehole fluid and diameter
- Water or mud filled open hole
- High vertical resolution

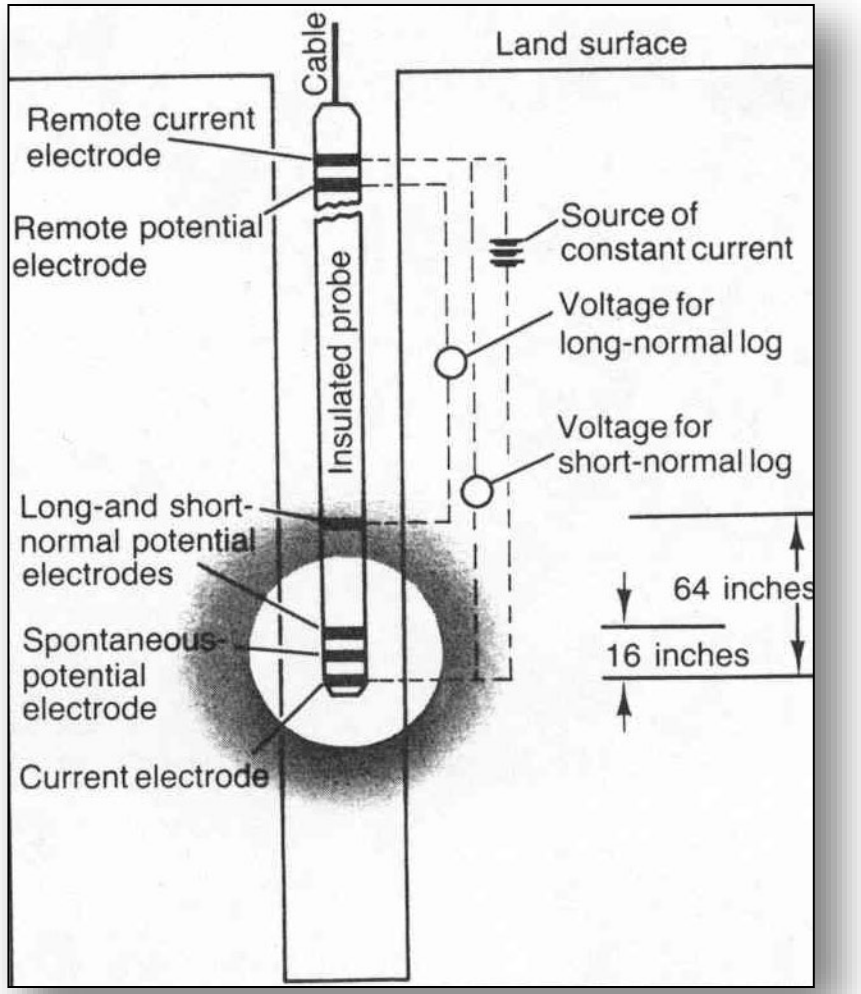


Keys (1990)

USGS

Normal Resistivity Log

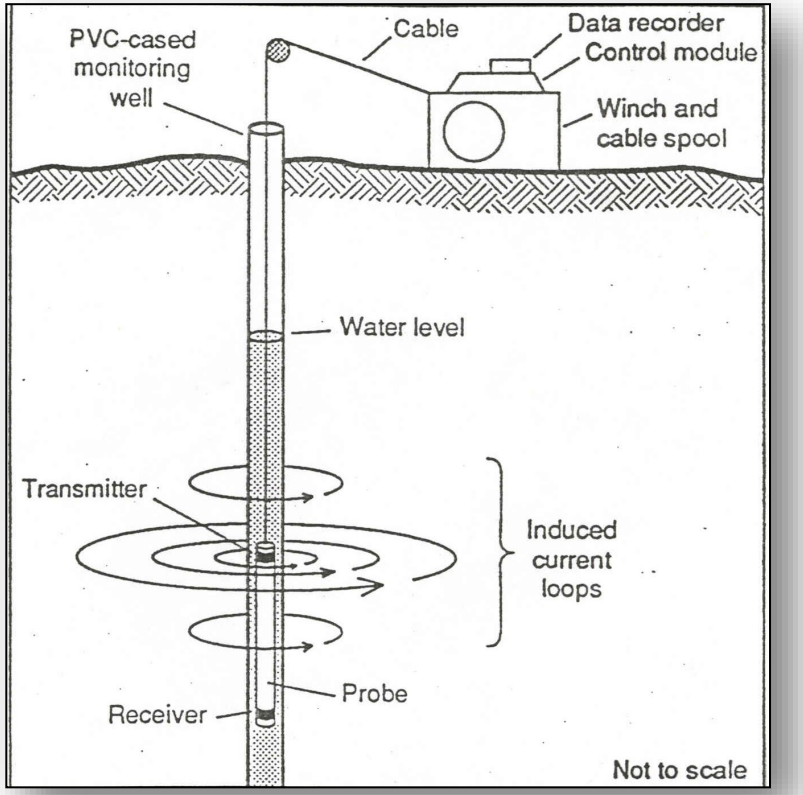
- Electrical resistivity of rocks and water
- Clay content, porosity, and dissolved solids
- Water or mud filled open holes
- Long and short normal



Keys (1990)

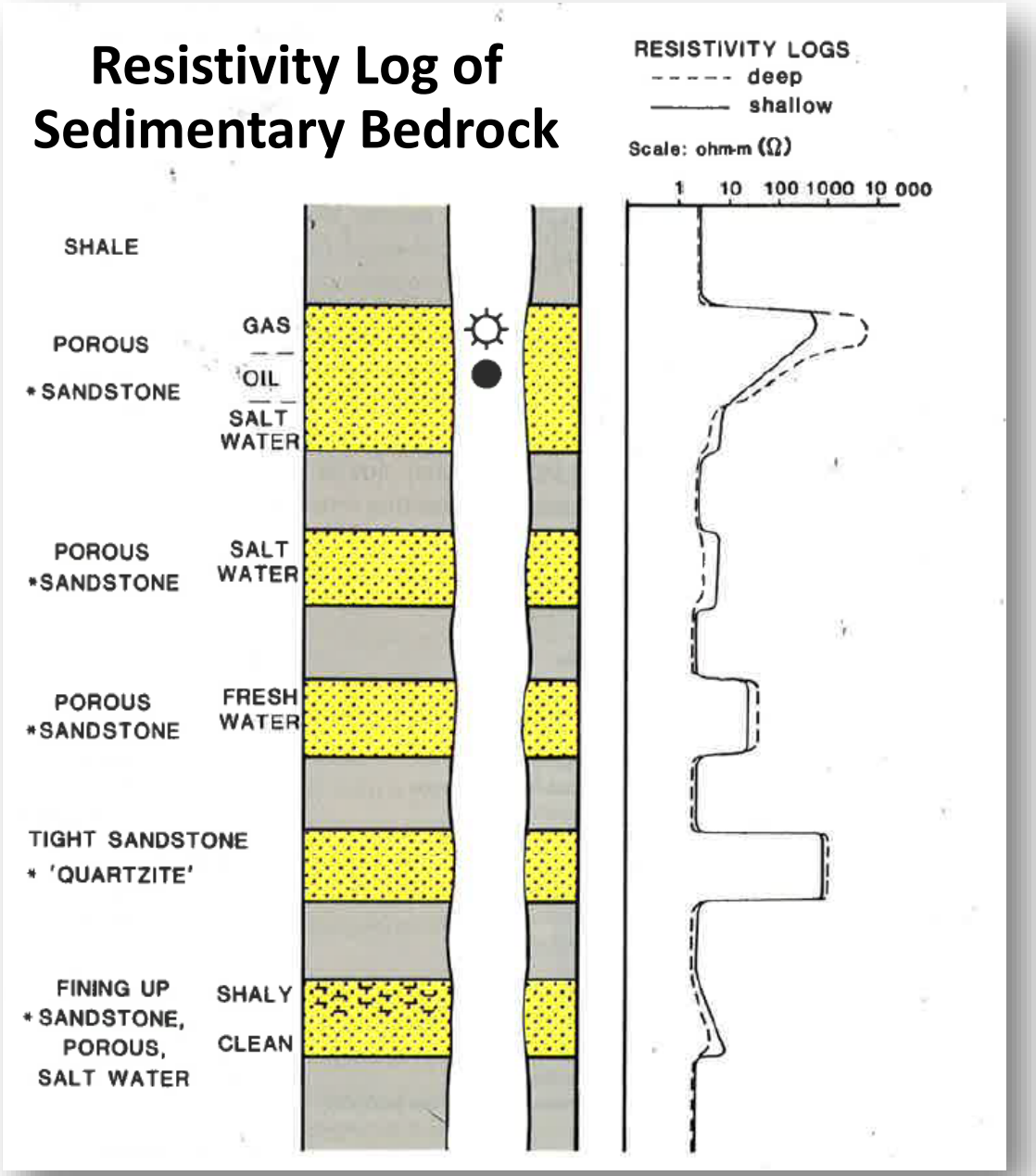
Electromagnetic Induction Log

- Widely used in the oil industry since 1950s
- Electrical conductivity/resistivity of rocks and water
- Clay content, porosity, and dissolved solids
- Air, water, or mud filled; open or PVC cased
- Not affected by borehole fluid
- High vertical resolution



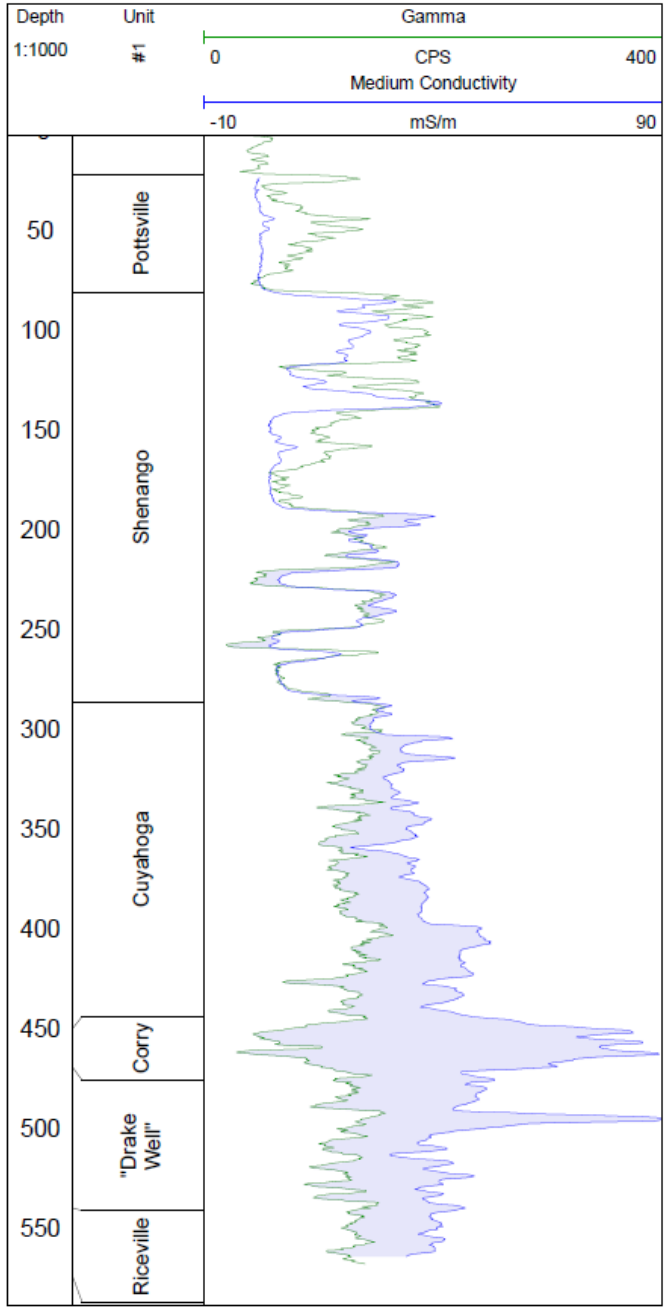
Williams and others (1993)

Resistivity Log of Sedimentary Bedrock



Rider and Kennedy (2011)

Oil well tophole in Allegheny Plateau sandstone and shale



Overlay of Gamma and Induction Conductivity

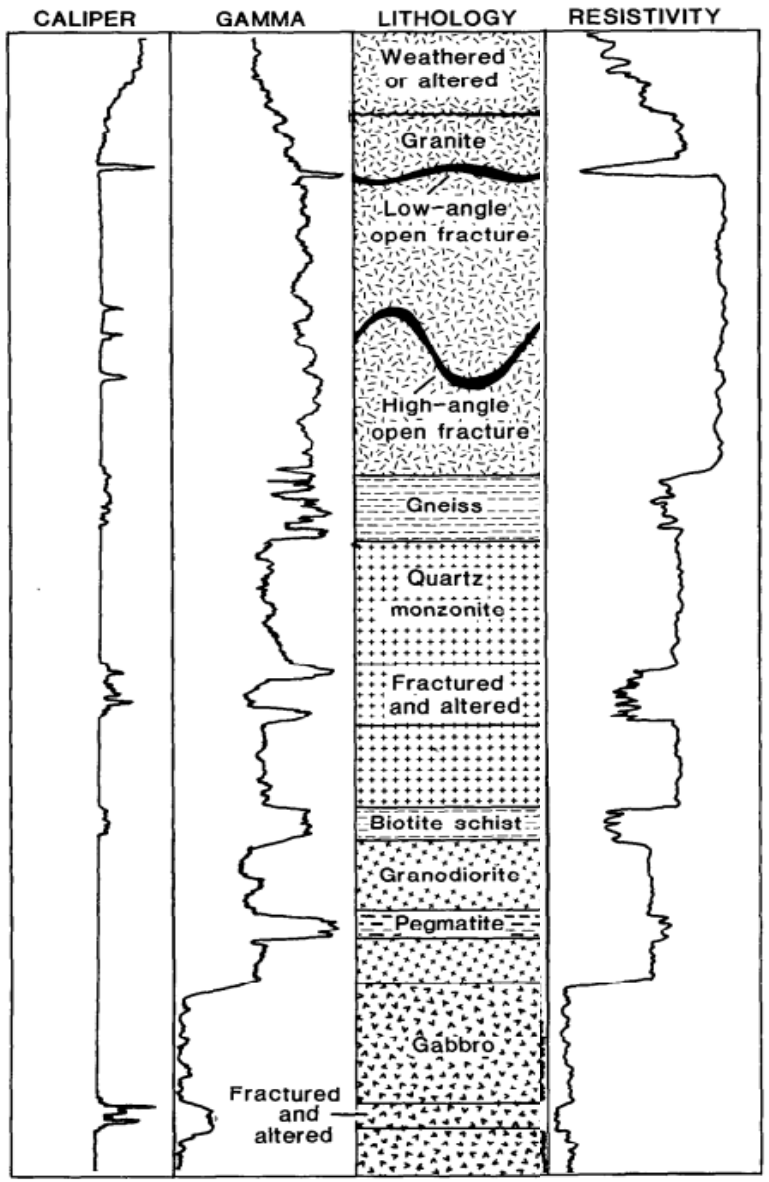
Low salinity in sandstone and shale

Increasing salinity in shale

High salinity in porous sandstone

Williams and others (2014)

Caliper, Gamma, and Resistivity Logs of Crystalline Bedrock

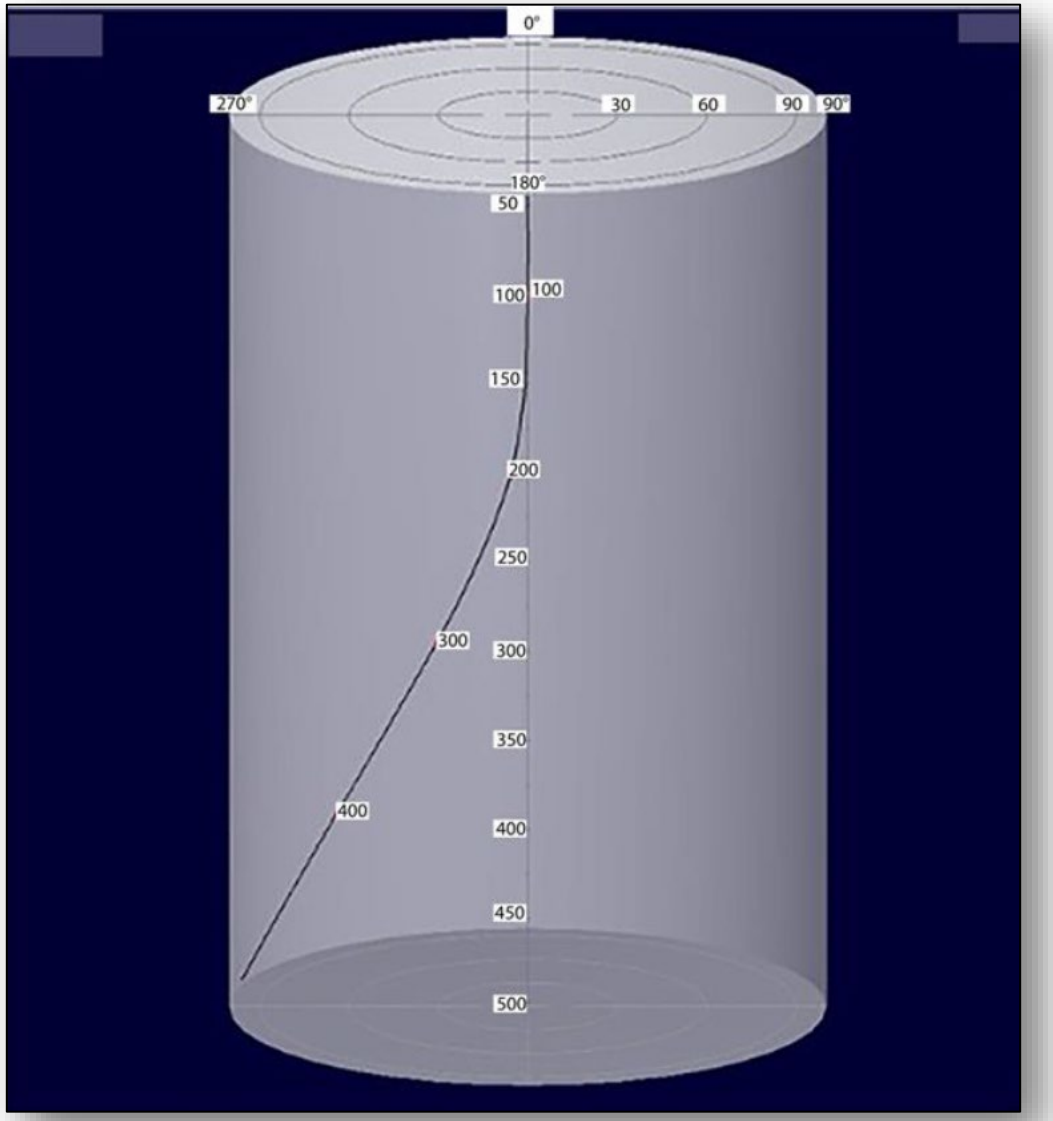


Keys (1990)

USGS

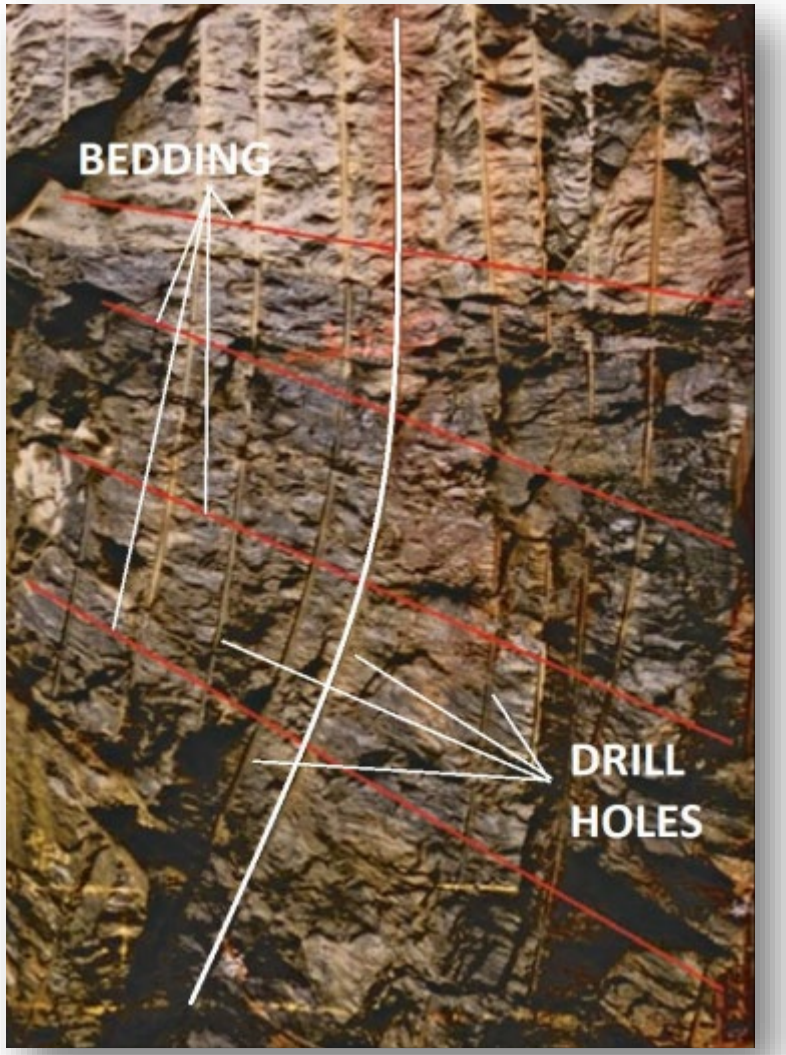
Deviation Log

- Measures borehole azimuth and tilt
- Used to calculate 3-dimensional path of the borehole
- Used to correct orientation of planar features identified on image logs
- Air, water or mud filled PVC-cased or open holes



Deviation of borehole in Hudson Highlands gneiss with eastward dipping metamorphic fabric (Reynolds and others, 2015)

USGS



Borehole Deviation

- Boreholes deviated from vertical
- Boreholes tend to deviate updip perpendicular to the bedrock fabric or layering (bedding, foliation, banding) (Brown and others, 1981)

USGS

Borehole Camera

- Fish-eye and side-wall view
- Typically, not oriented
- Direct viewing of lithology, bedding, foliation, fractures, and flow
- Water- or air-filled holes
- Affected by water clarity

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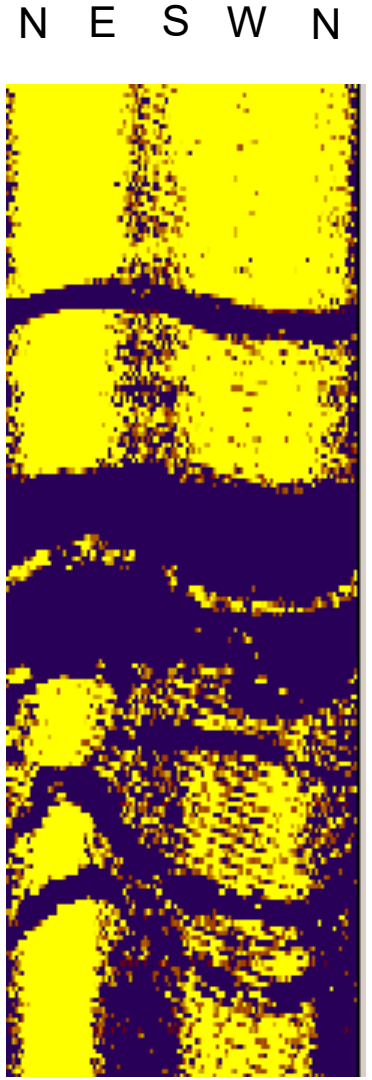
Acoustic Televiewer

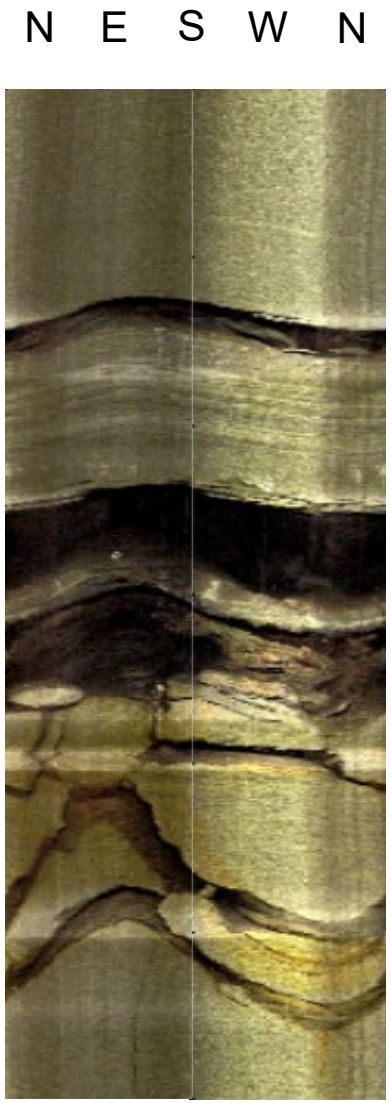
- Ultrasound pulse-echo system
- Acoustic amplitude and transit time
- Oriented 360-degree acoustic image of borehole wall
- Acoustic reflectivity related to lithology, bedding, foliation, and fractures
- Water- or light mud-filled holes



USGS

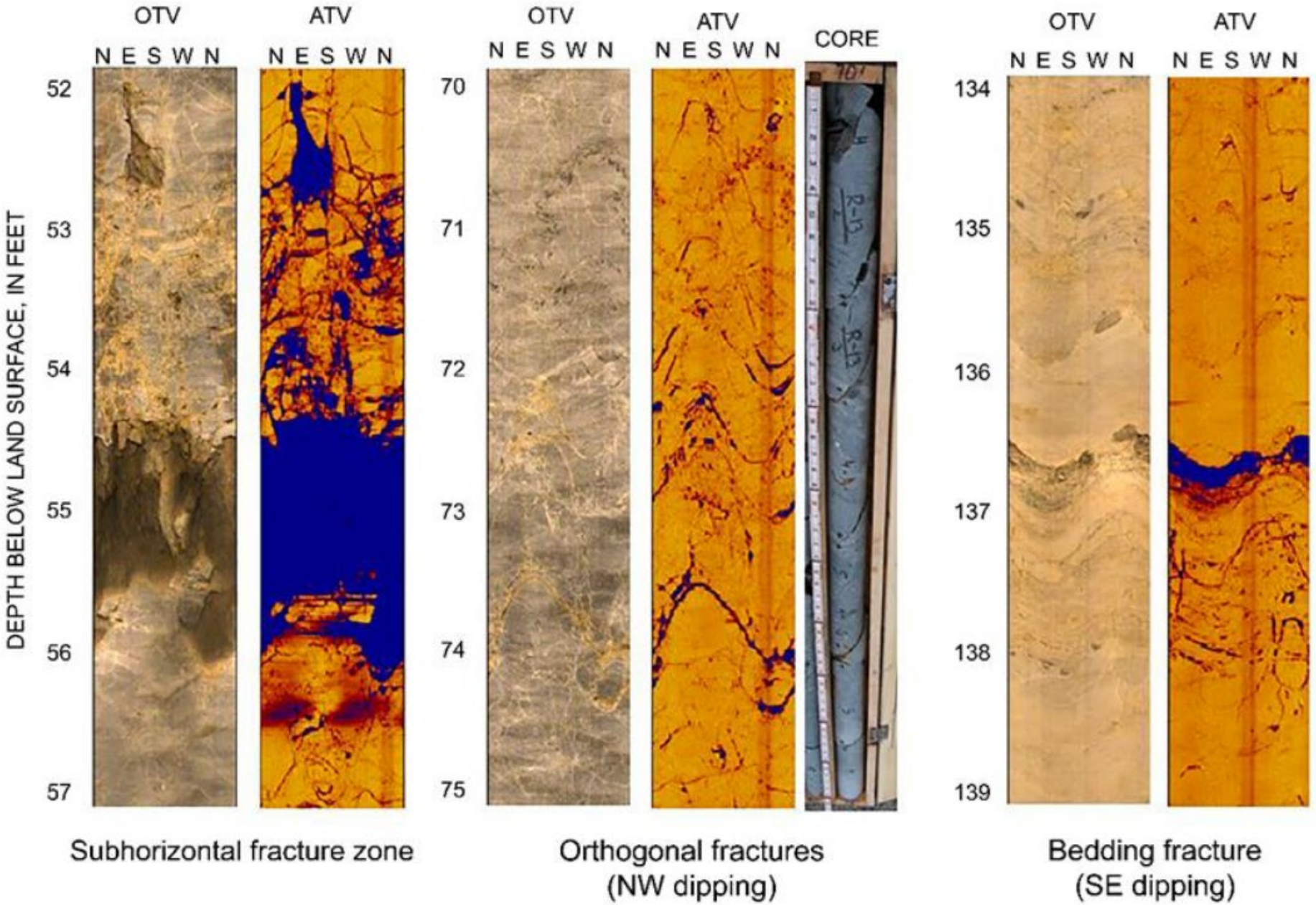
Optical Televiewer

- CCD camera with conical or hyperbolic reflector
- Oriented 360 degree optical image of borehole wall
- Direct viewing of lithology, bedding, foliation, and fractures
- Water- or air-filled holes
- Less affected by water clarity than fisheye



USGS

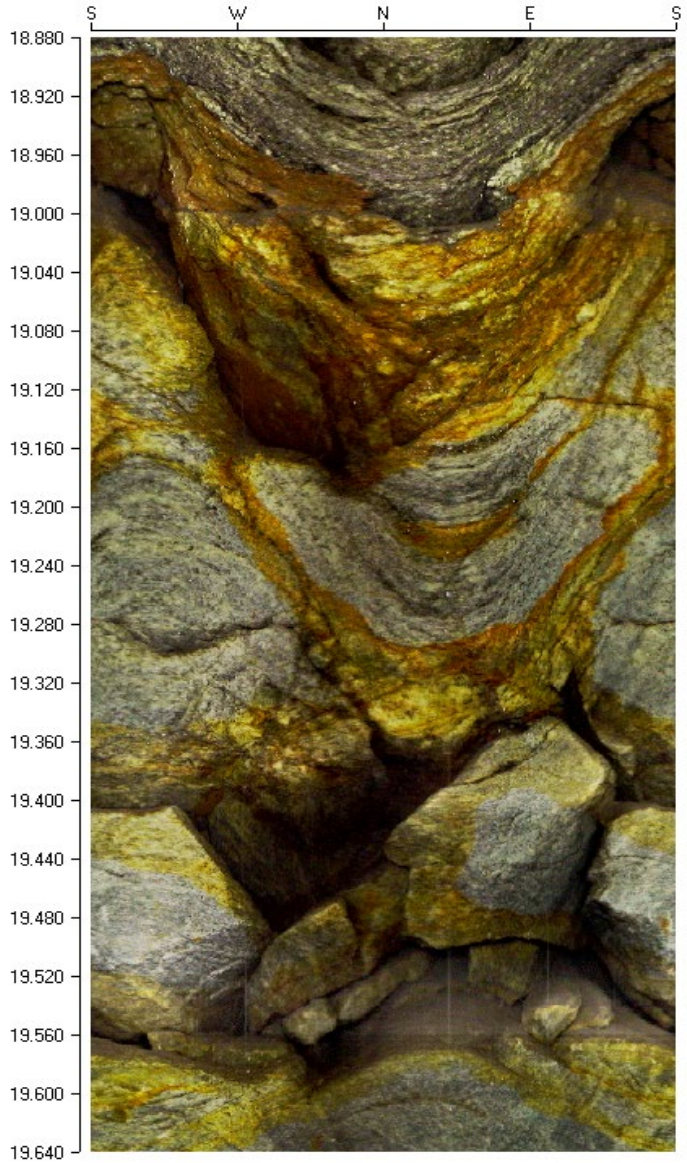
Monitoring well in Hudson Highlands marble



USGS

Monitoring well in gneiss

Unwrapped OTV Image

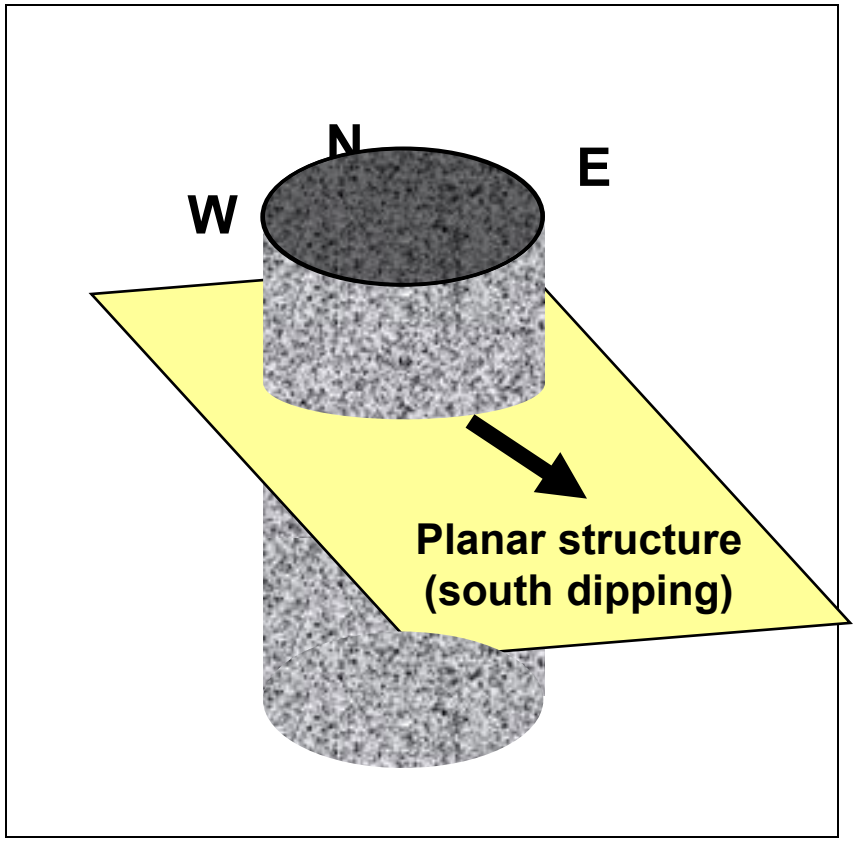


Virtual Core

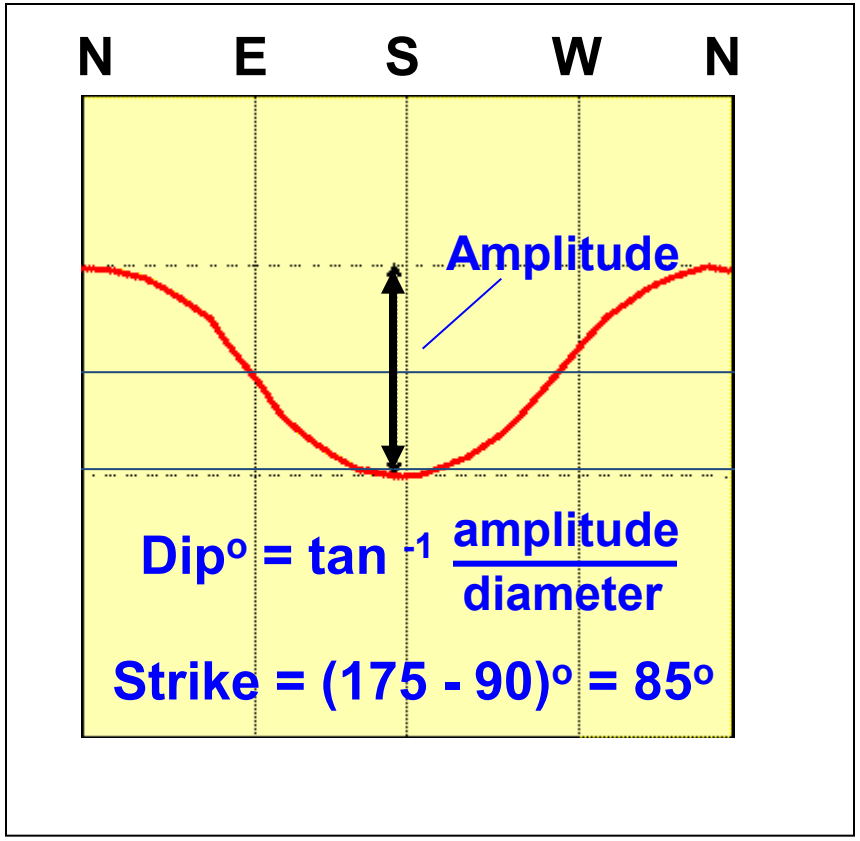
Johnson and others (2002)

Borehole-Wall Image Analysis

3-D wrapped image



Unwrapped image



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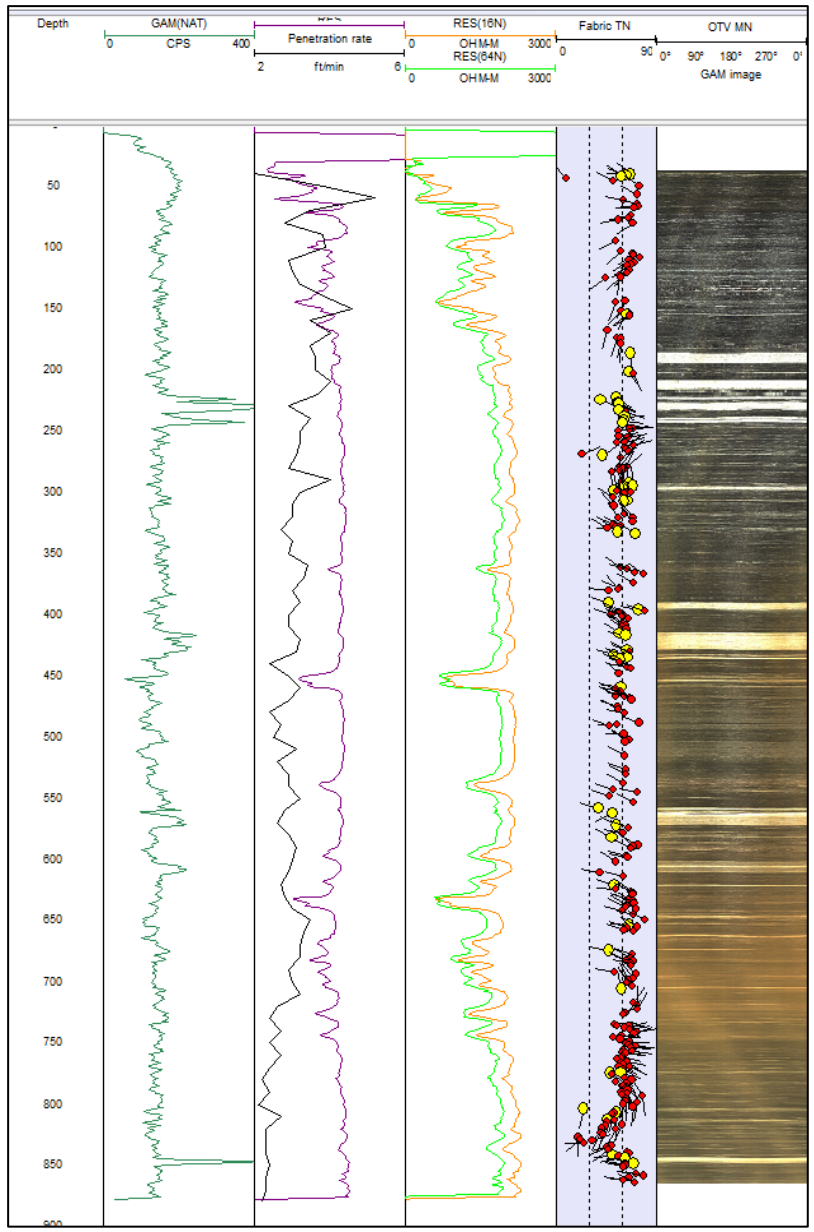
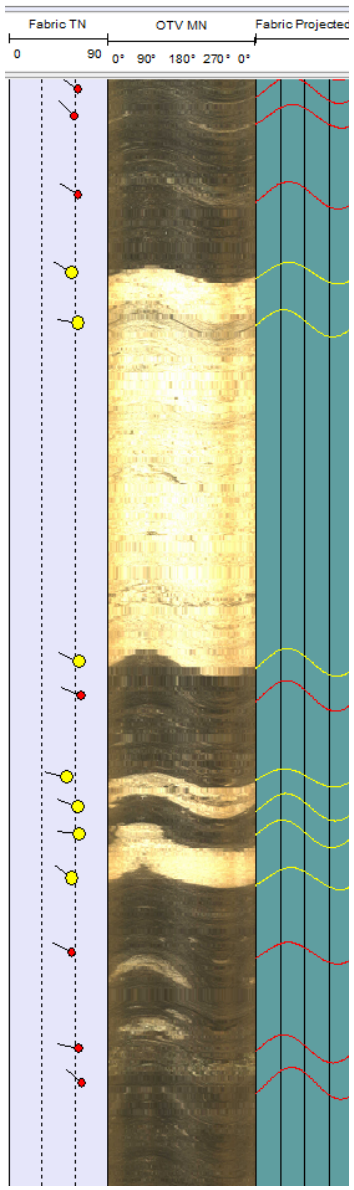


Foliation

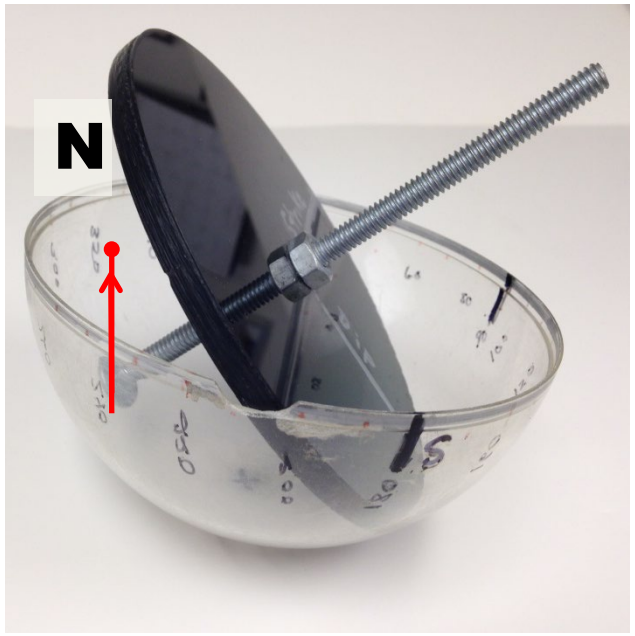
Tadpoles

Projections

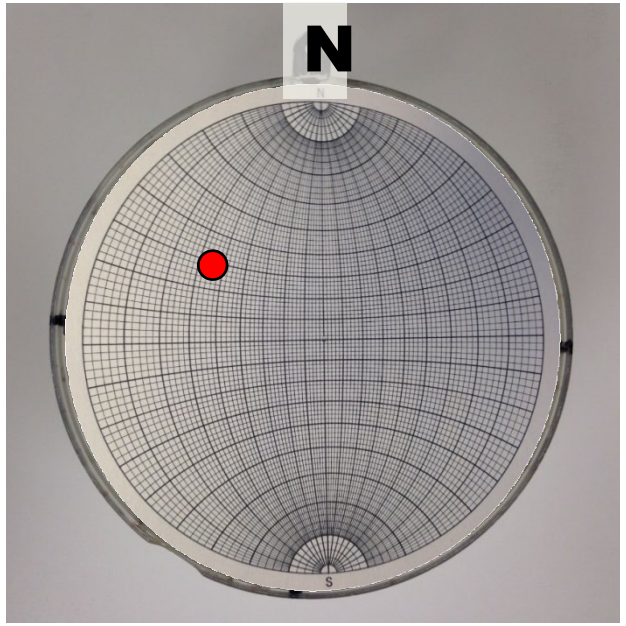


Geothermal test borehole in Manhattan Prong schist

Stereonet Plot – Lower Hemisphere



Pole to the plane is the point where the pole (perpendicular to the plane) intersects the lower hemisphere and is projected up to the plotting circle



Point shown on the plotting circle.
Planar features are reduced to points in the stereographic projection

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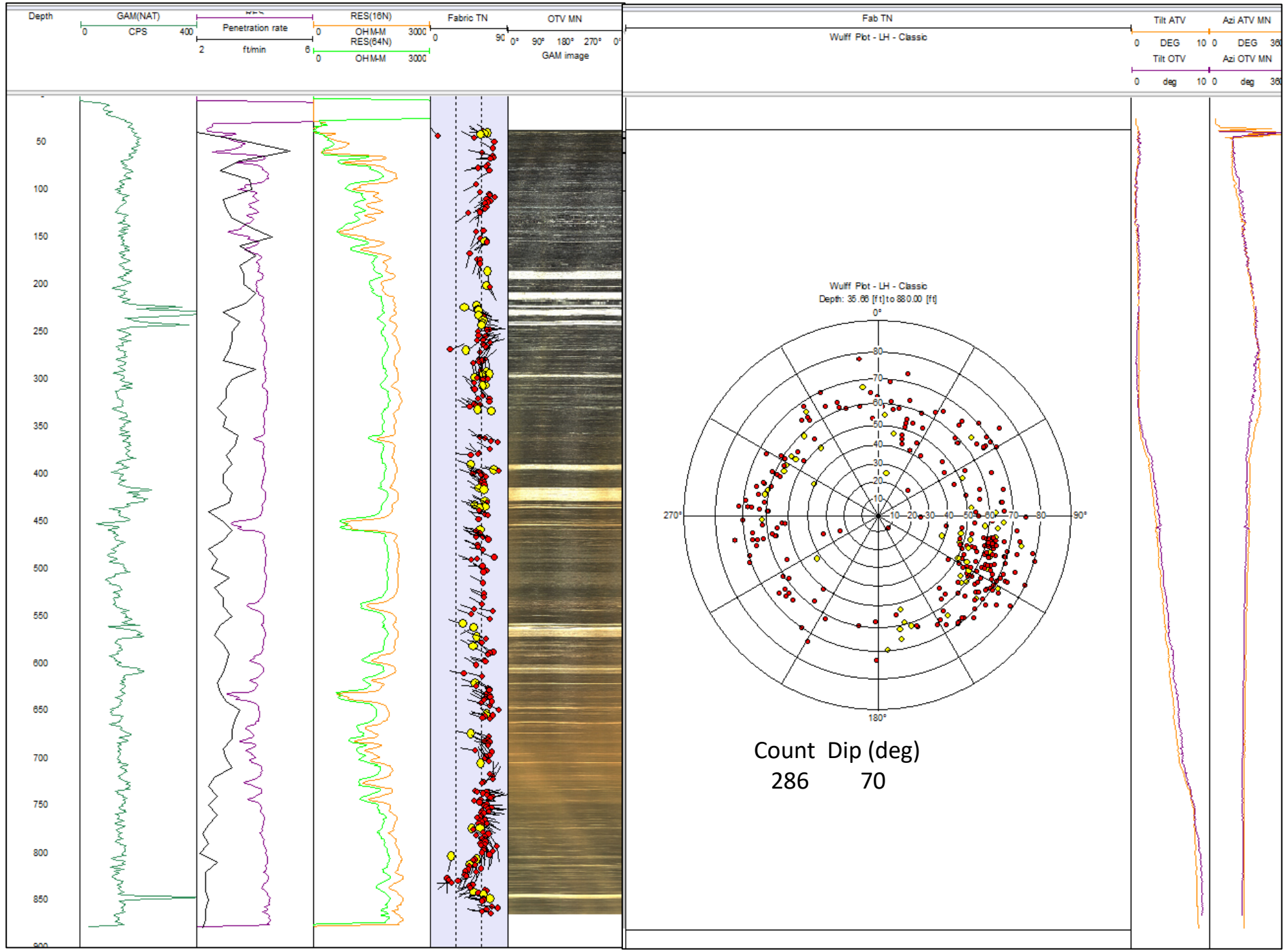
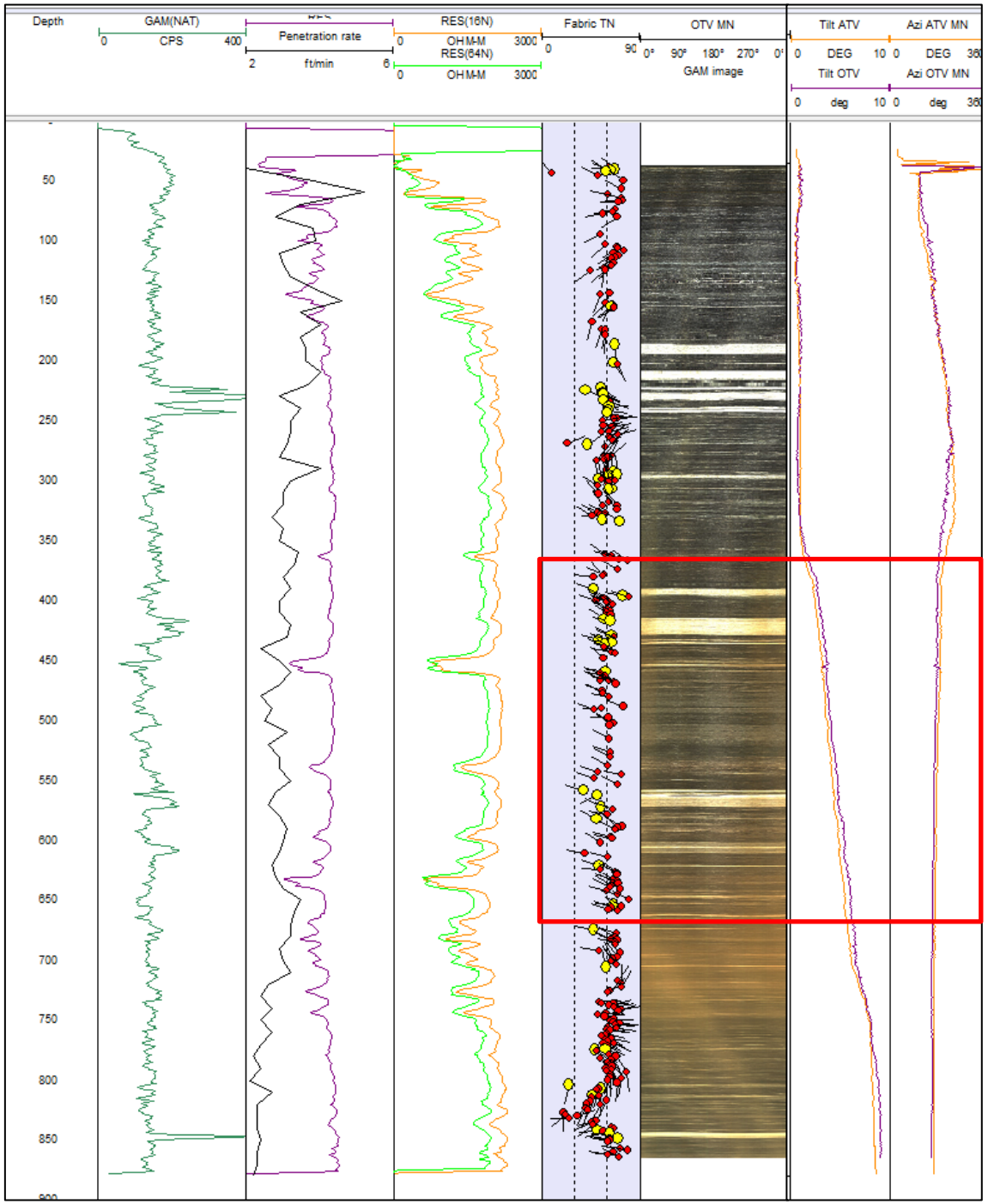


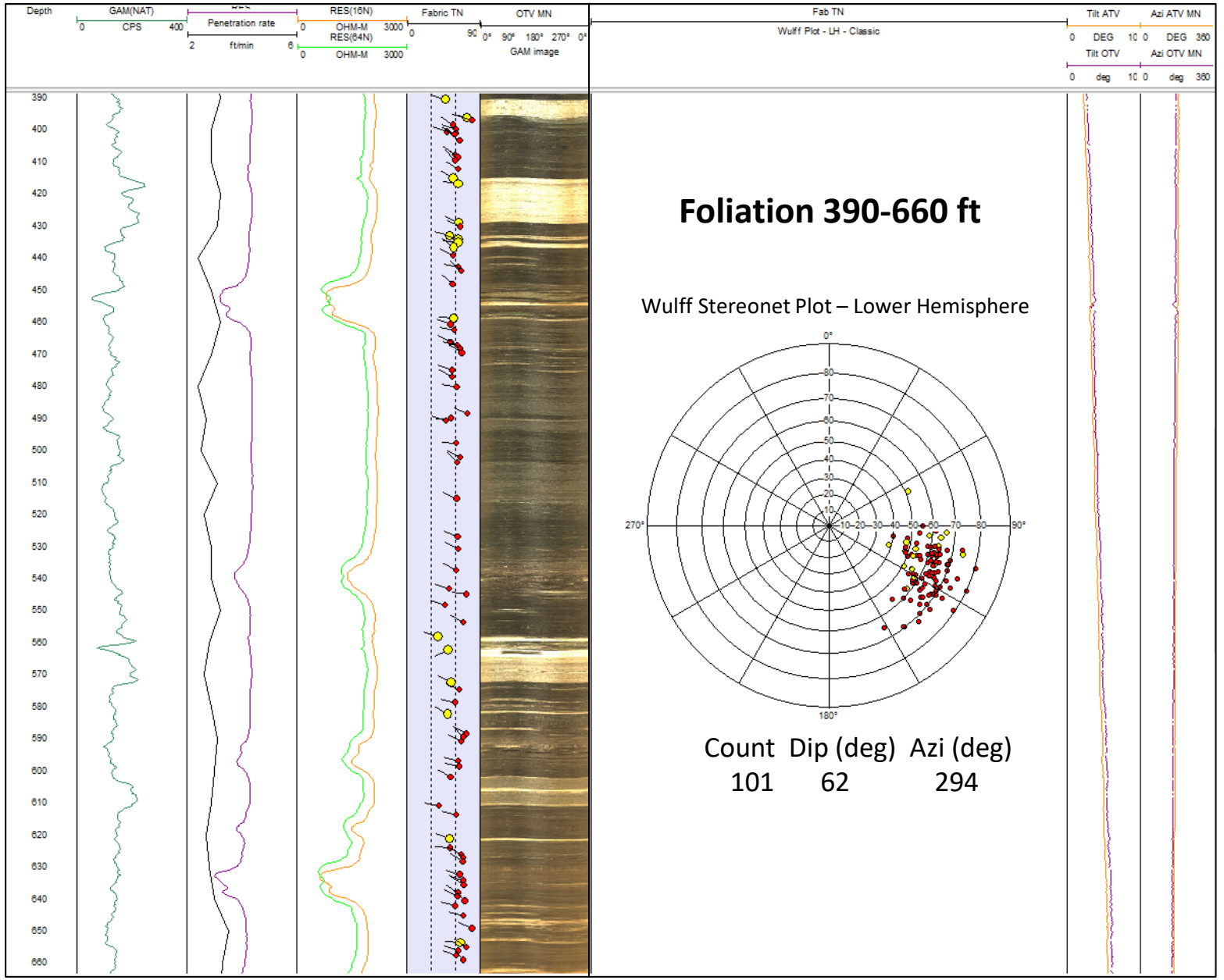
Count Dip (deg)
286 70

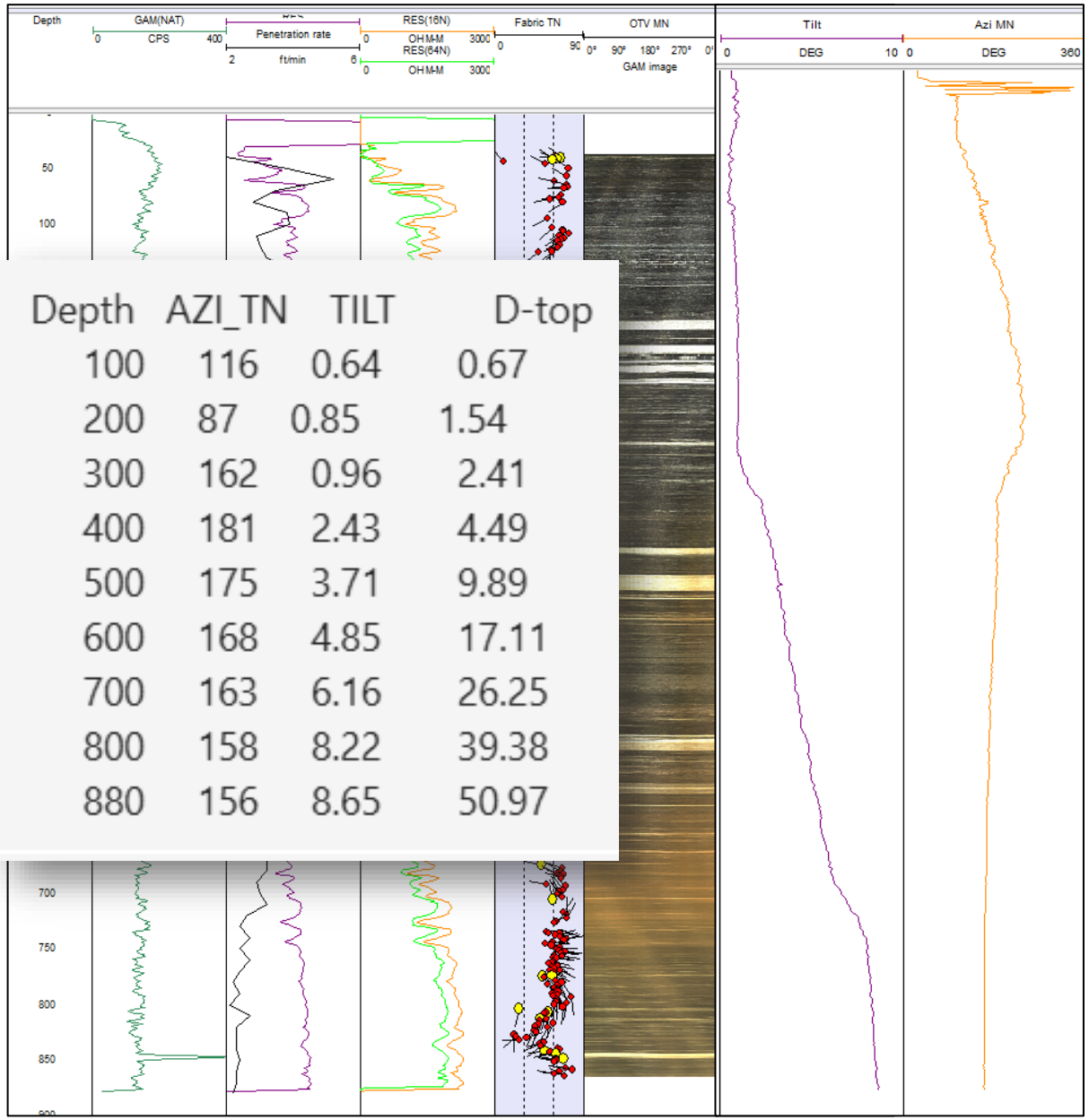
USGS



Foliation 390-660 ft

Count	Dip (deg)	Azi (deg)
101	62	294

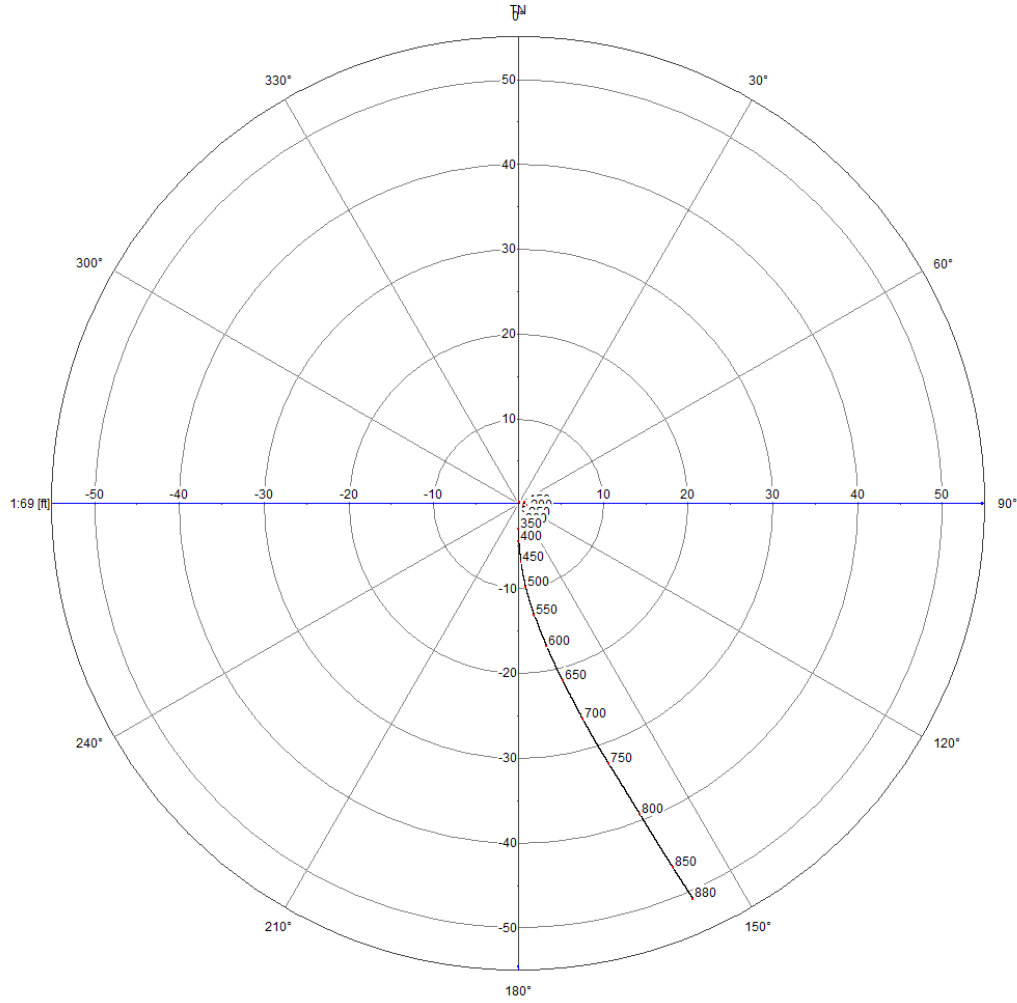




Depth	AZI_TN	TILT	D-top
100	116	0.64	0.67
200	87	0.85	1.54
300	162	0.96	2.41
400	181	2.43	4.49
500	175	3.71	9.89
600	168	4.85	17.11
700	163	6.16	26.25
800	158	8.22	39.38
880	156	8.65	50.97

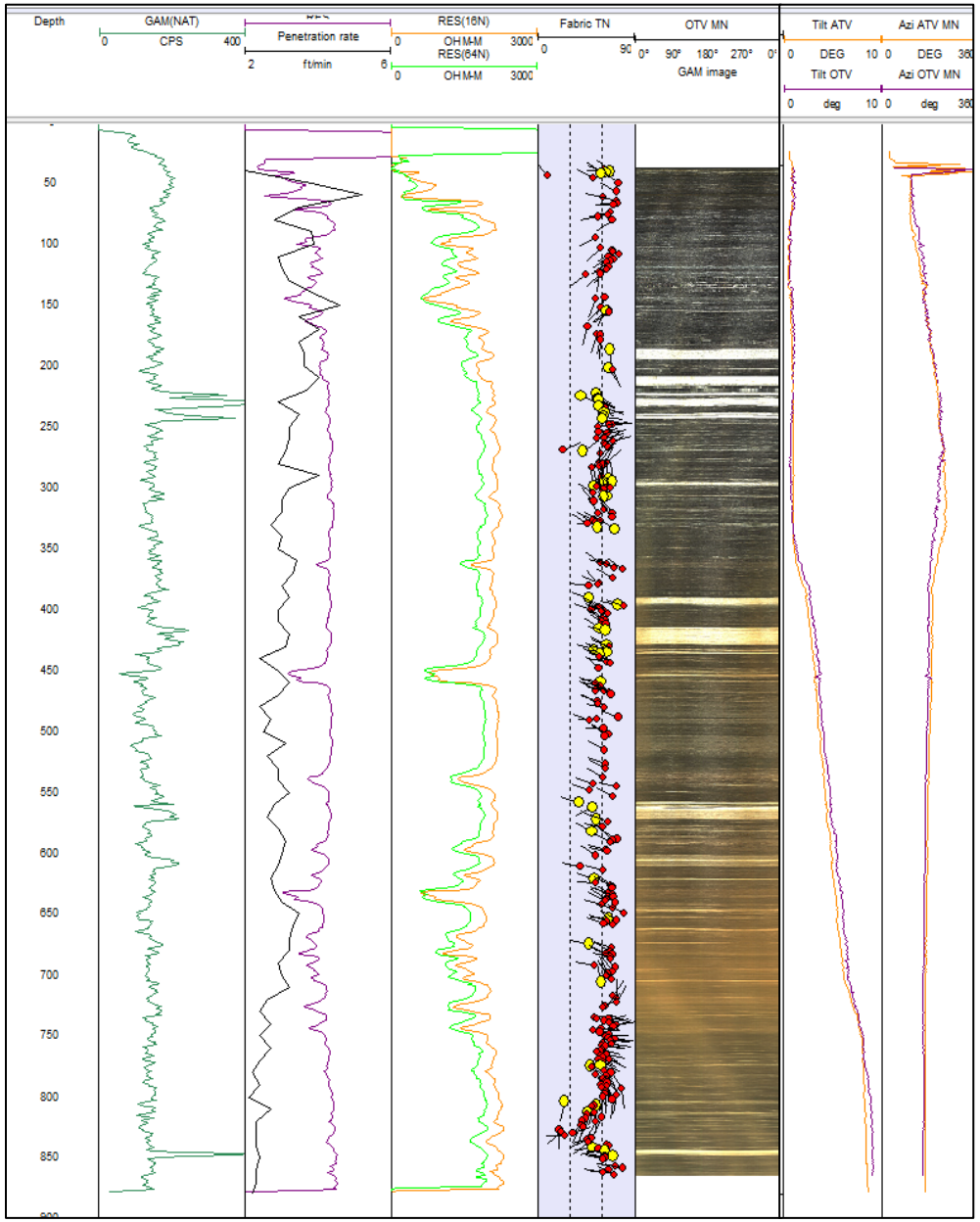
Borehole Deviation

Bulls Eye Plot



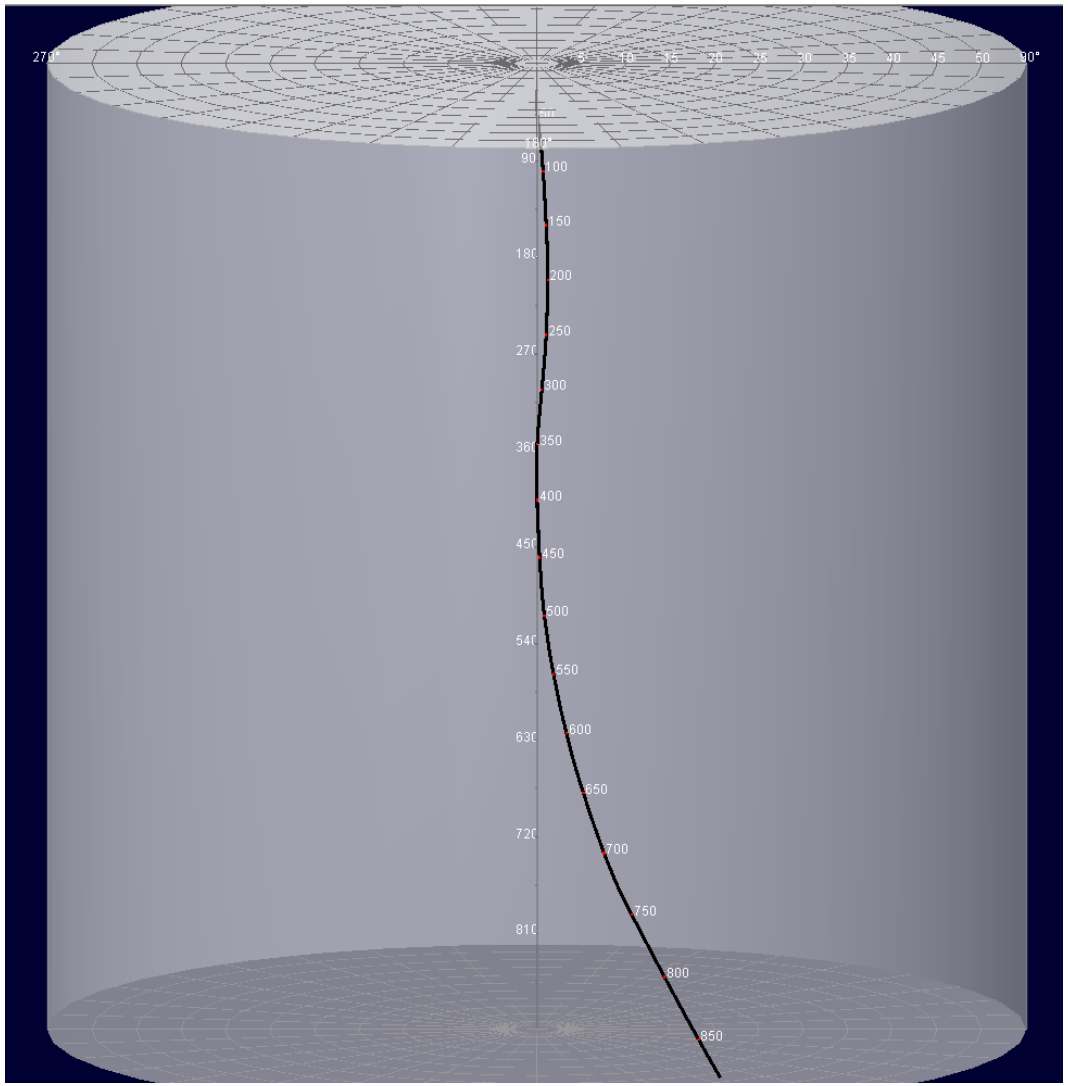
USGS

USGS

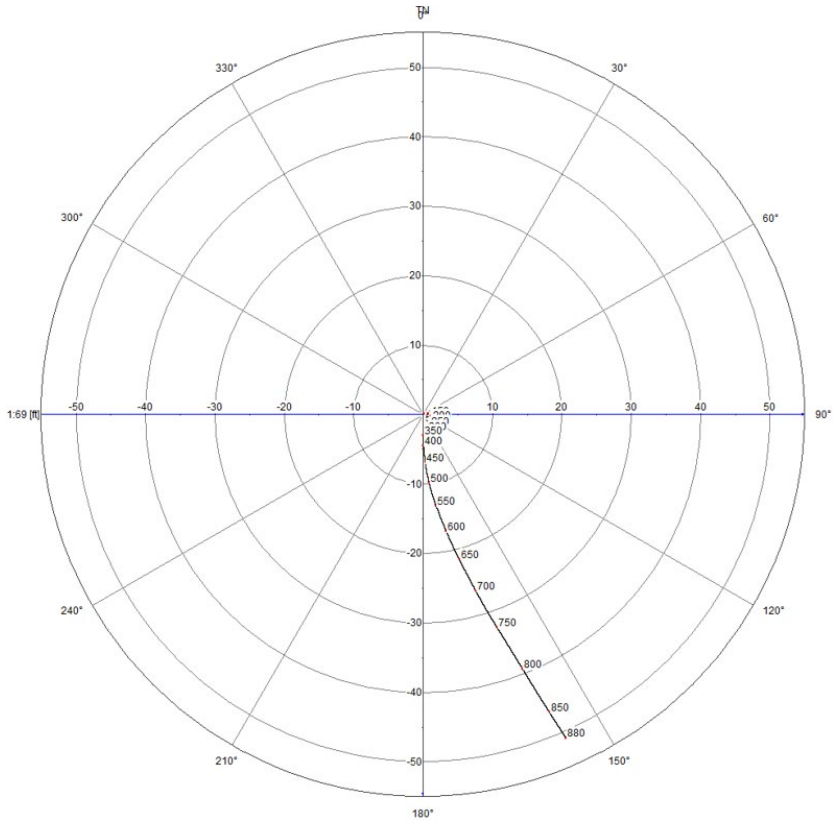


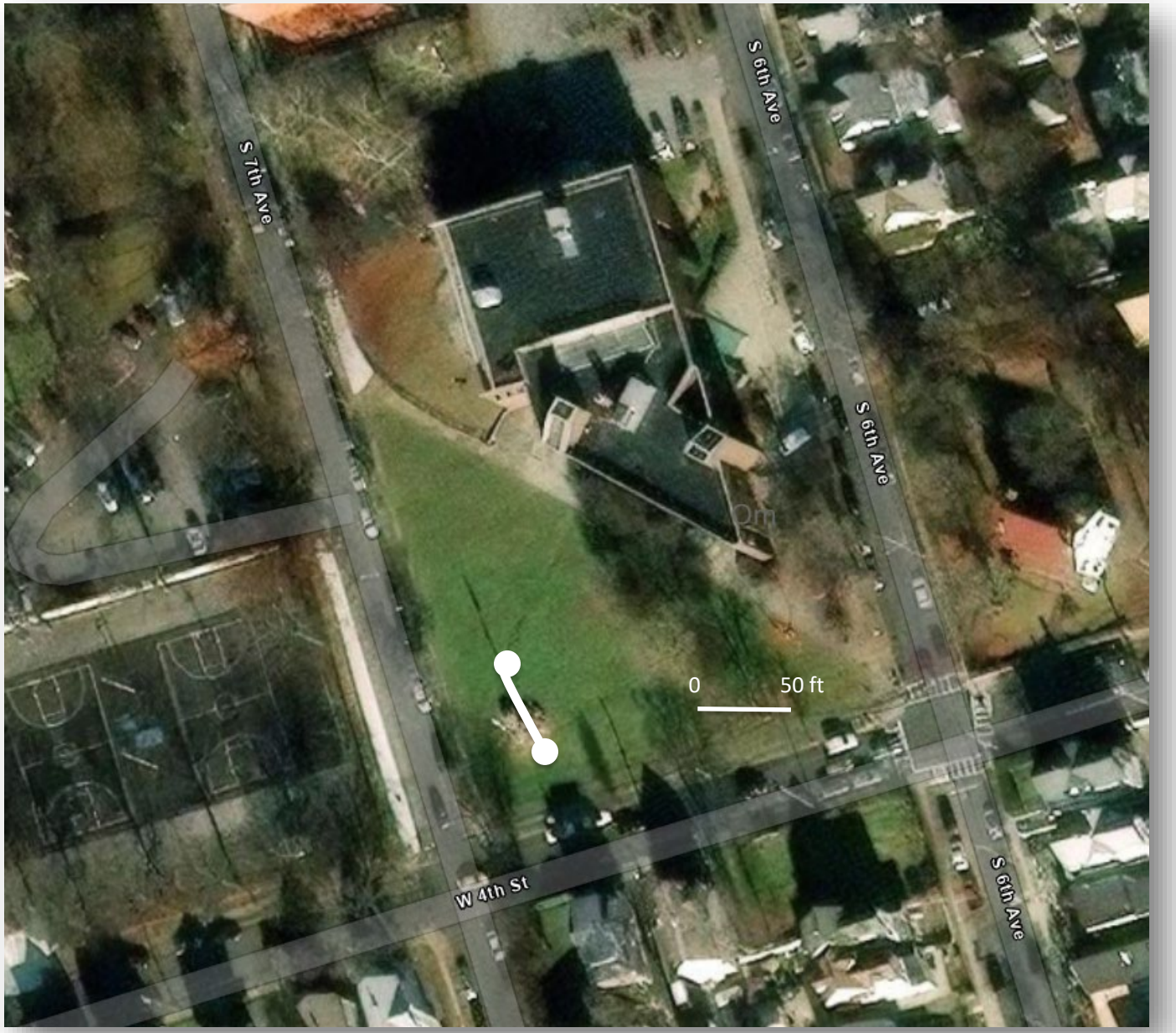
Borehole Deviation

3D Cylindrical Plot



Borehole Deviation Path





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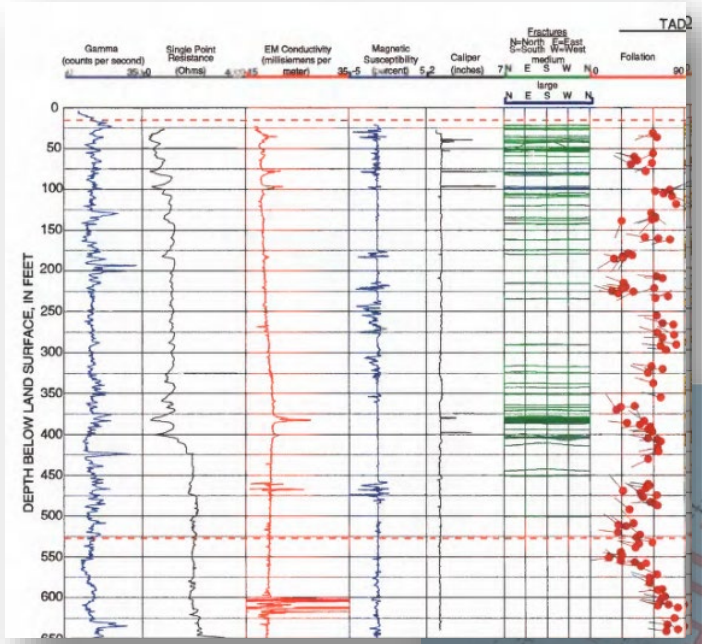
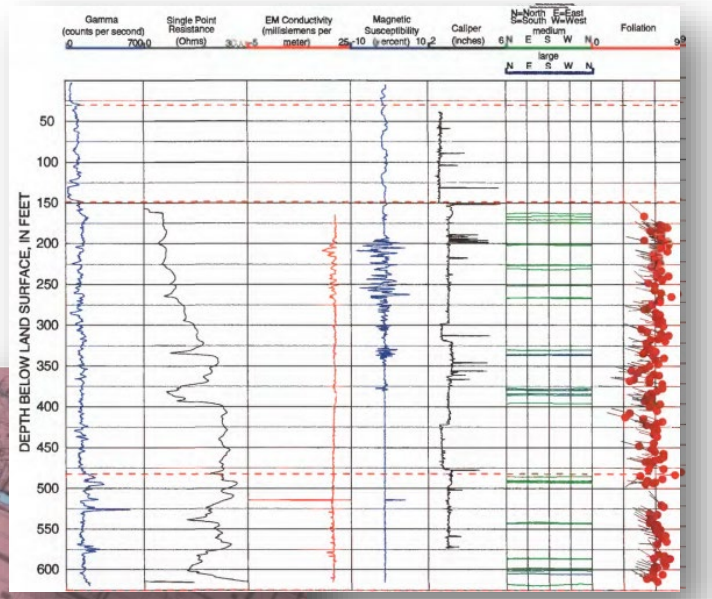
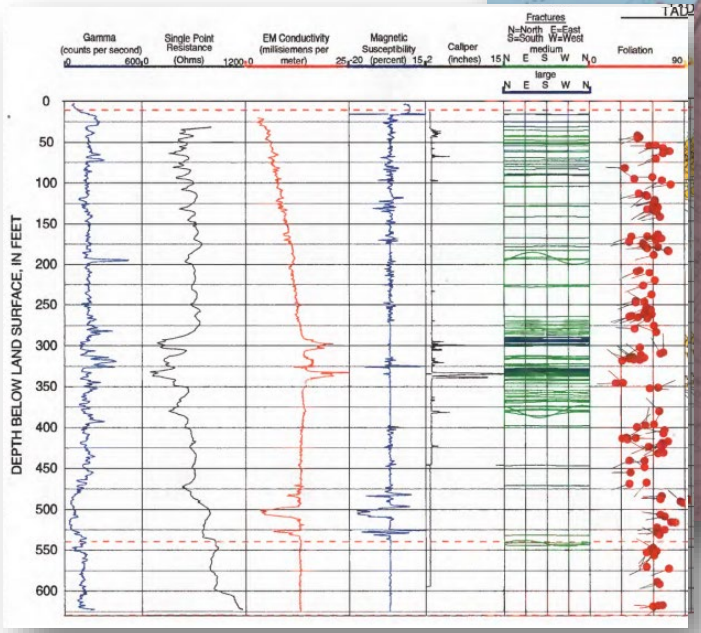
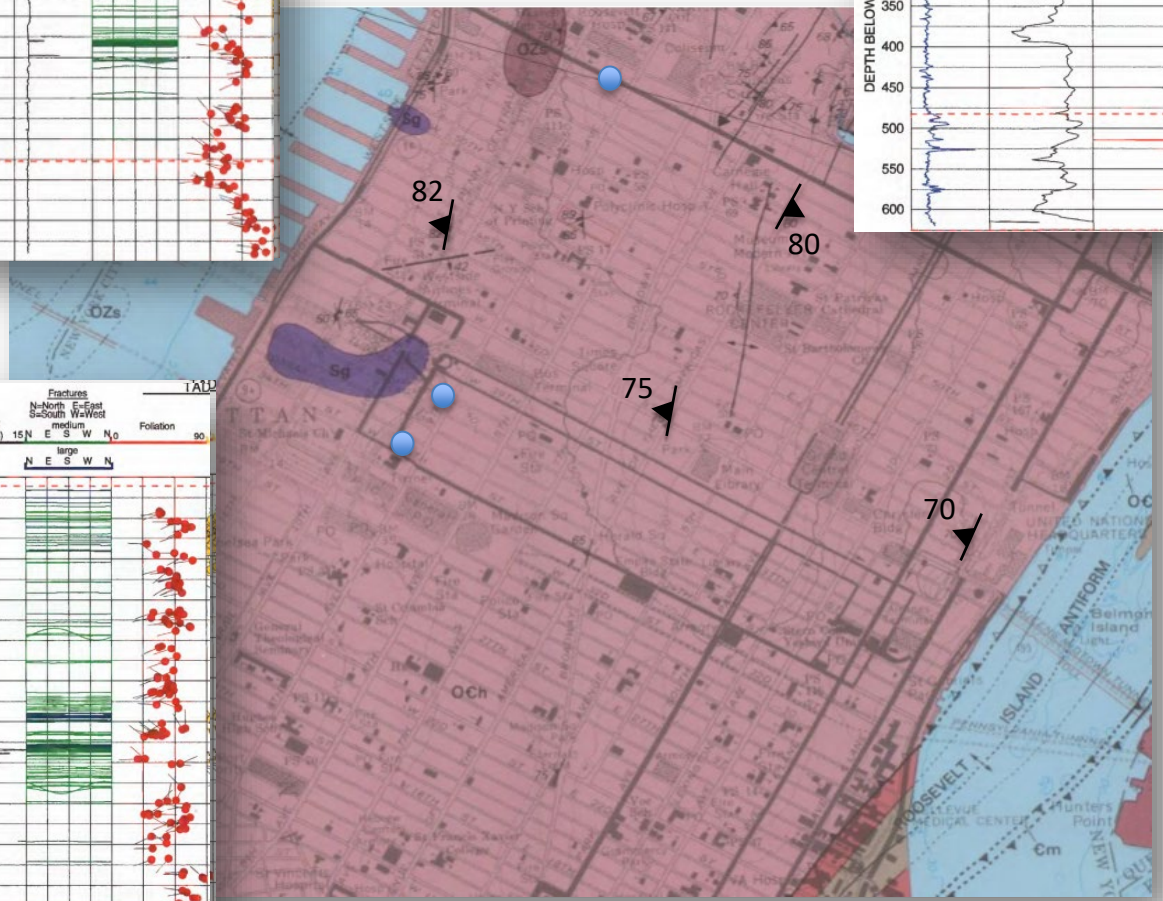




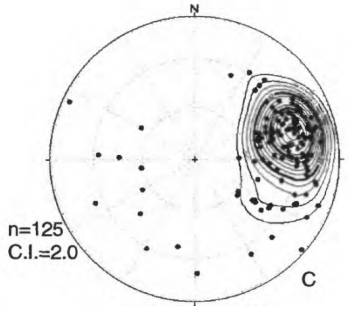
Stumm and others, 2001

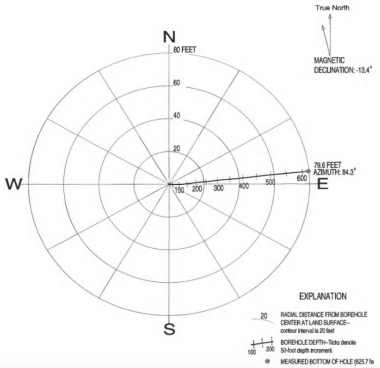


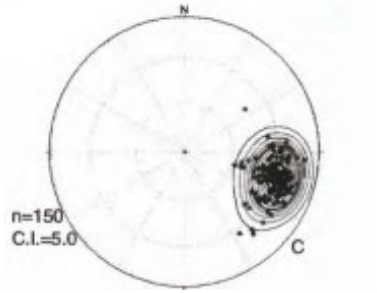


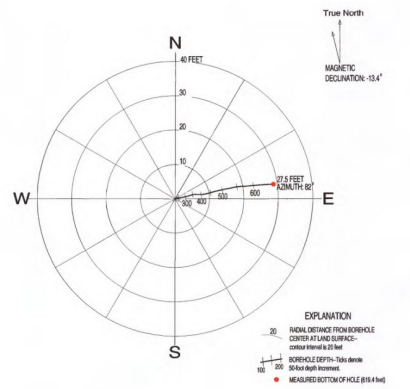
Baskerville, 1994

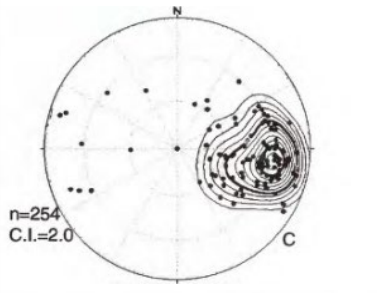
USGS











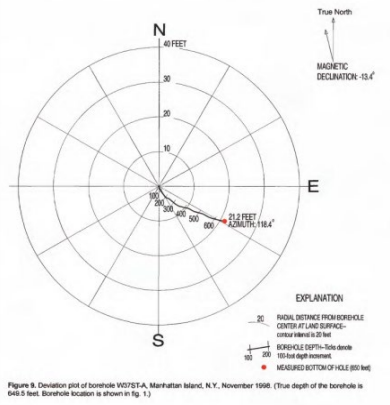


Figure 9. Deviation plot of borehole W07ST-A, Manhattan Island, N.Y., November 1998. (True depth of the borehole is 649.5 feet. Borehole location is shown in fig. 1.)

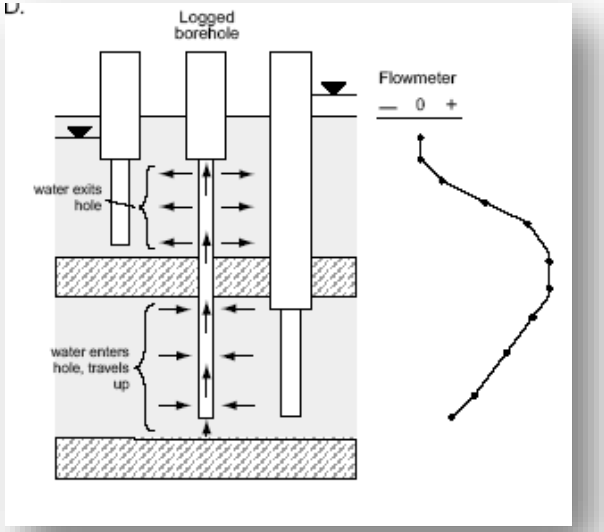
USGS

Baskerville, 1994

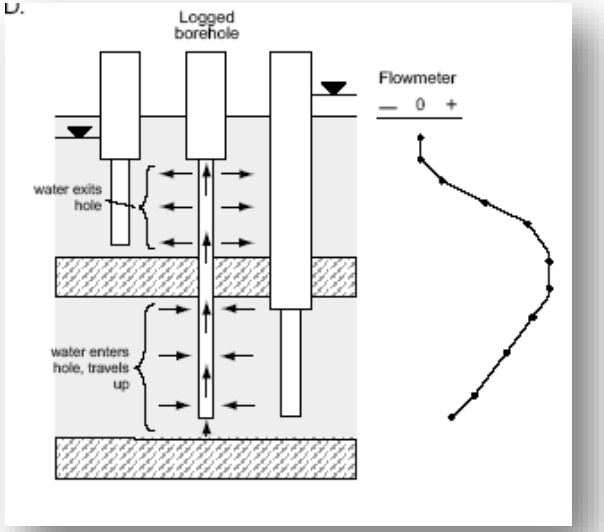
Stumm and others, 2001

Ambient Flow and Fluid-Property Logs

- Deep boreholes typically penetrate multiple flow zones that have differing hydraulic head
- Vertical flow occurs from zones of higher hydraulic head to zones of lower hydraulic head under ambient conditions
- Flow and fluid-property logs are collected under ambient conditions to determine the direction and rate of flow between producing and receiving zones



Downward Flow

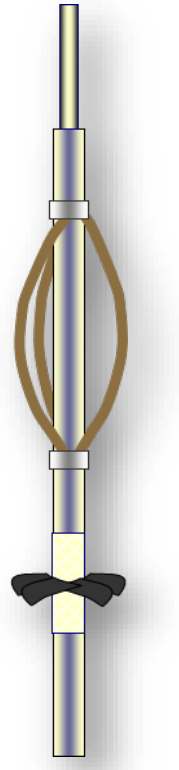


Upward Flow

USGS

Flowmeters

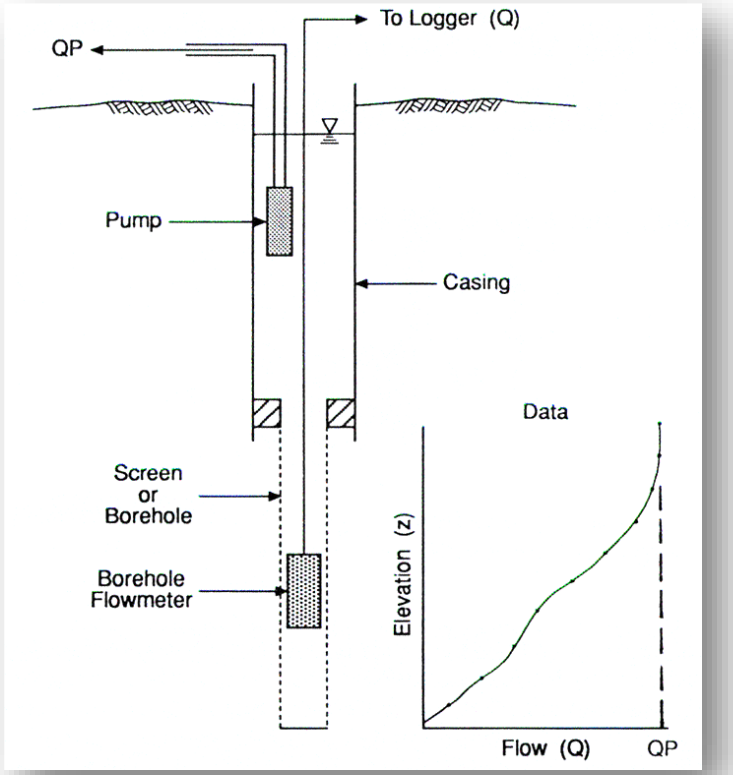
- Spinner flowmeter
  - Stationary and trolling measurements
  - Measurement range 5 to 5000 gal/min
- Heat-pulse flowmeter
  - Stationary measurements
  - Tool with diverter 0.005 to 1.5 gal/min
  - Tool without diverter 0.5 to 5 gal/min
- Electromagnetic flowmeter
  - Stationary and trolling measurements
  - Tool with diverter 0.05 to 15 gal/min
  - Higher flows with underfit or no diverter
  - Fluid resistivity and temperature sensors



USGS

Pumped Flow and Fluid-Property Logs

- Flow and fluid-property logs are repeated under steady-state drawdown pumped conditions
- Pumped flow log, pumping rate, and drawdown are analyzed using FLASH to estimate flow-zone transmissivity and hydraulic head (Day-Lewis and others, 2011)



USGS

Upward Ambient Flow

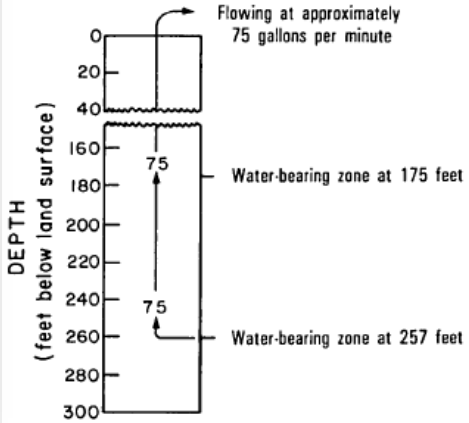
Valley and Ridge sandstone and shale

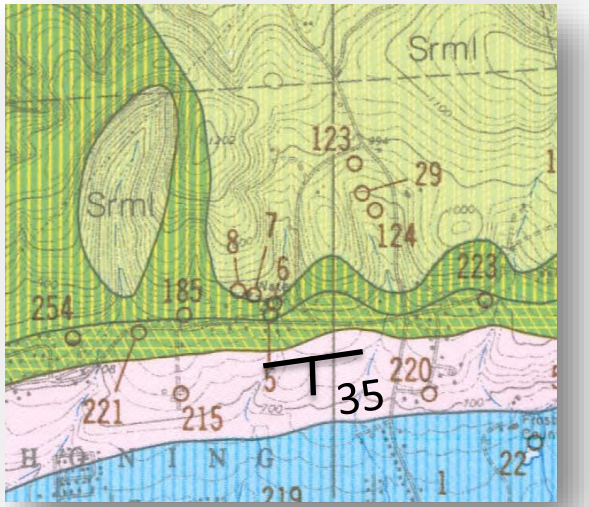
Well number: Mt–29

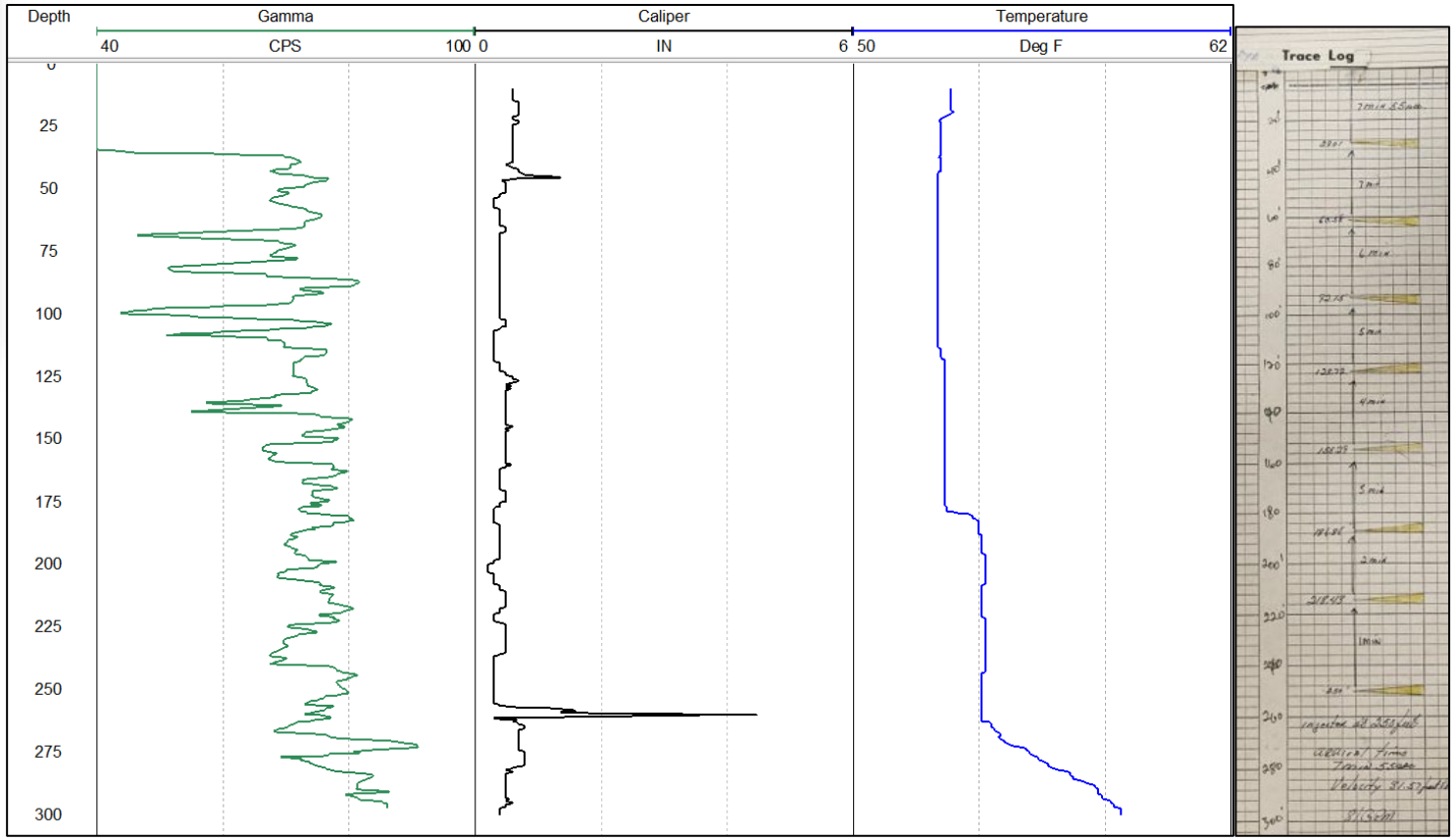
Geologic unit: Lower member of the Rose Hill Formation

Topographic setting: Upland draw

Well depth: 300 feet







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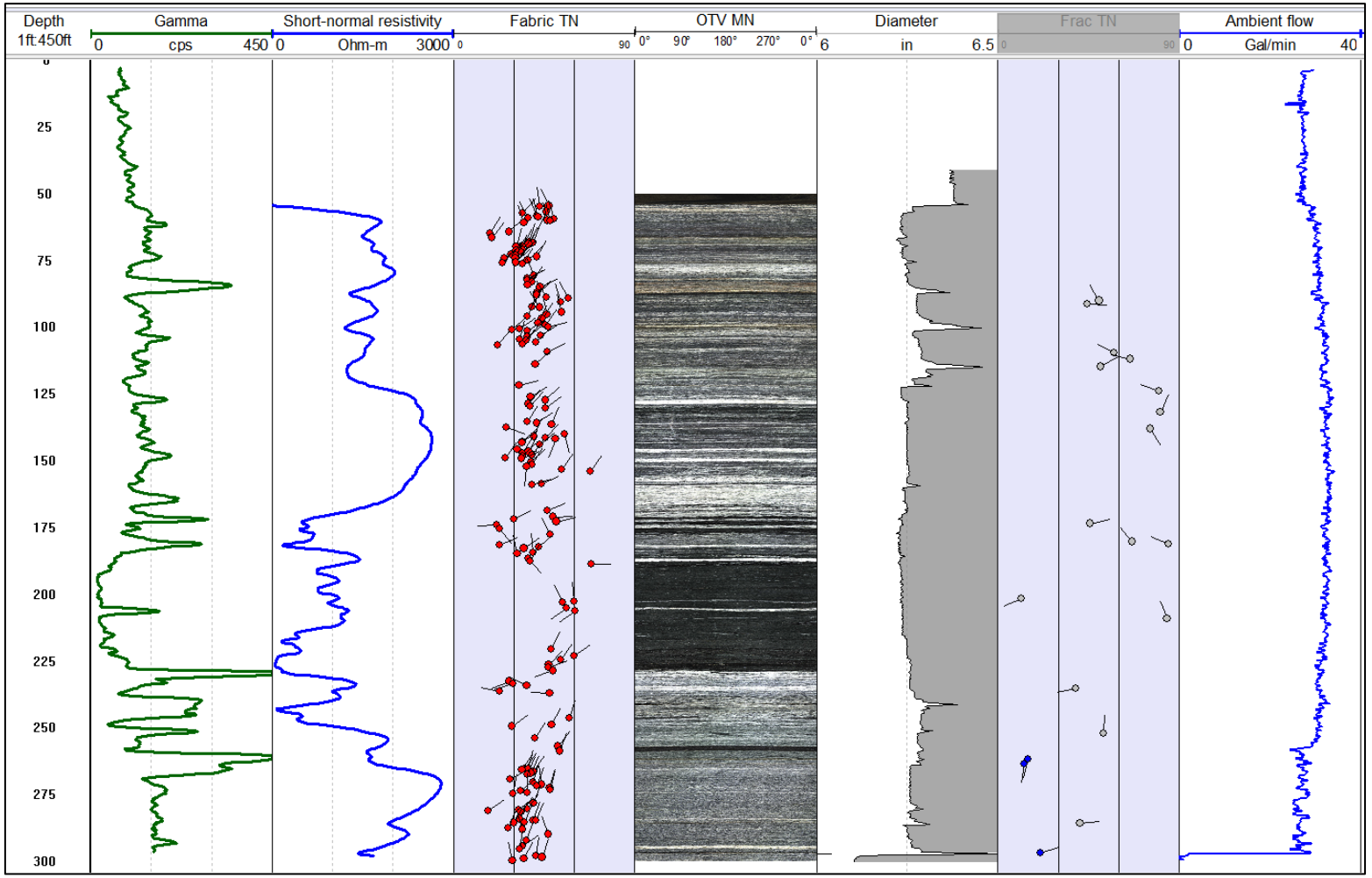
Wisconsin Geological and Natural History Survey
DIVISION OF EXTENSION
UNIVERSITY OF WISCONSIN–MADISON

Upward Ambient Flow

Hudson Highlands gneiss



Subhorizontal fractured zone at 297 ft

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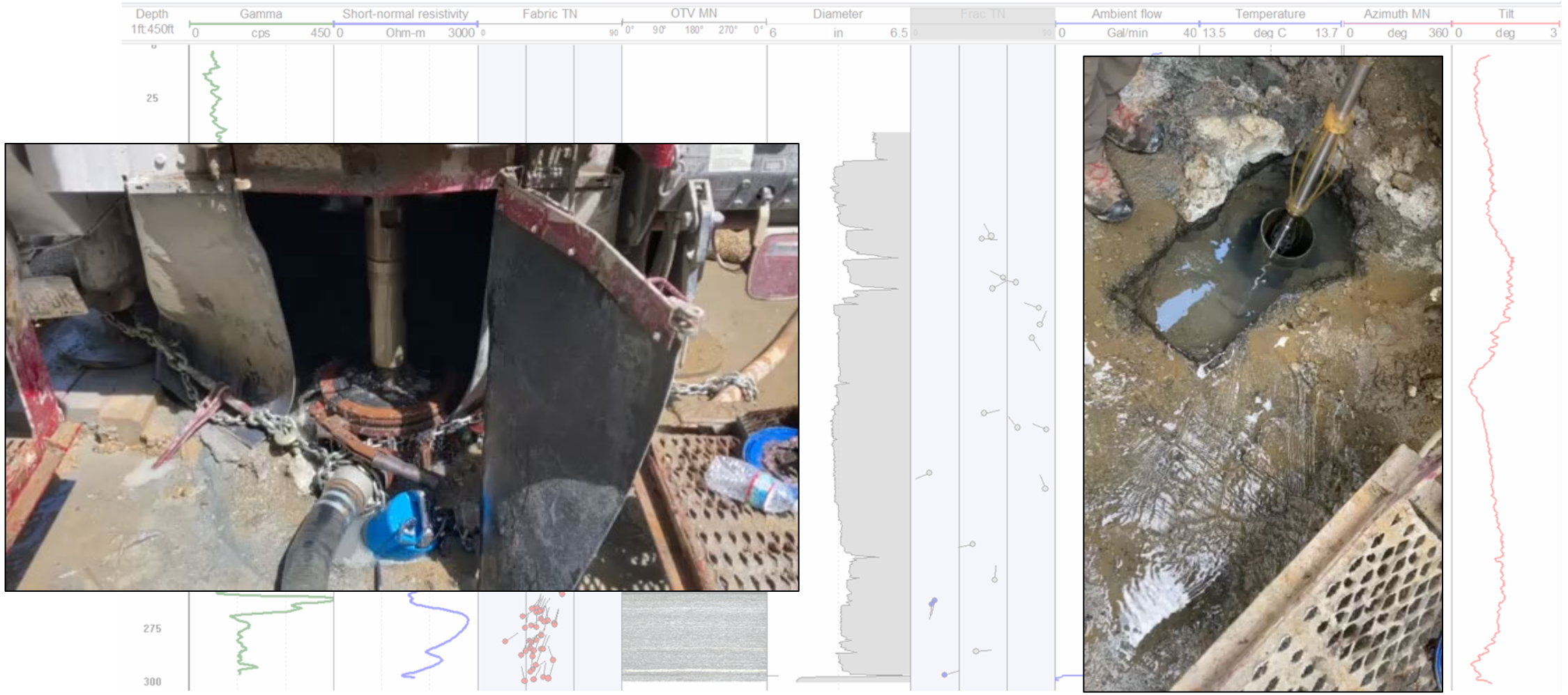
UNIVERSITY OF WISCONSIN–MADISON

Upward Ambient Flow

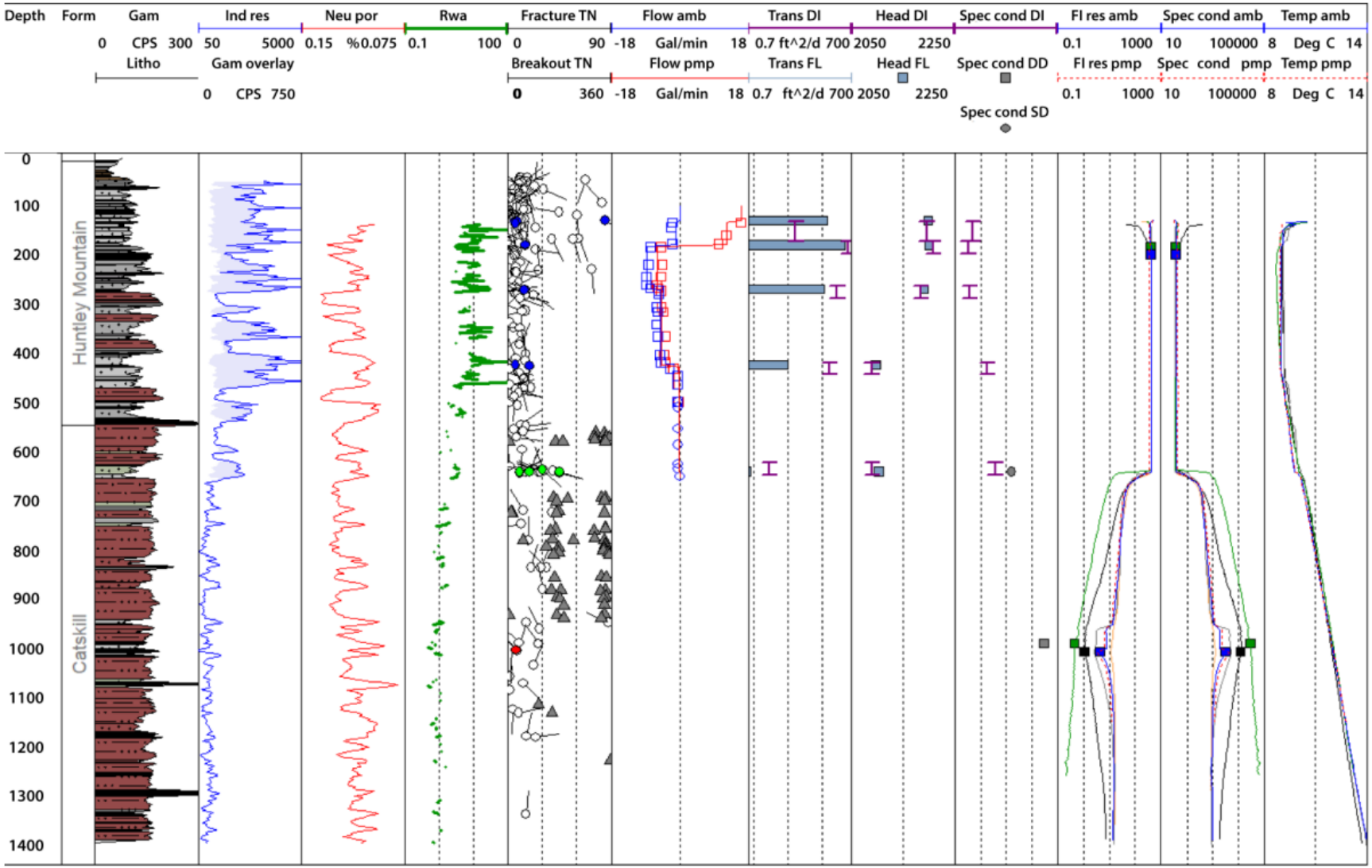
Hudson Highlands gneiss



USGS

Downward Ambient Flow

Allegheny Plateau sandstone and shale



USGS

Risser, Williams, Hand, and others (2013)
Williams, Risser, and Dodge (2015)
Risser, Williams, and Bierly (2021)

Freshwater Inflow Zones

USGS

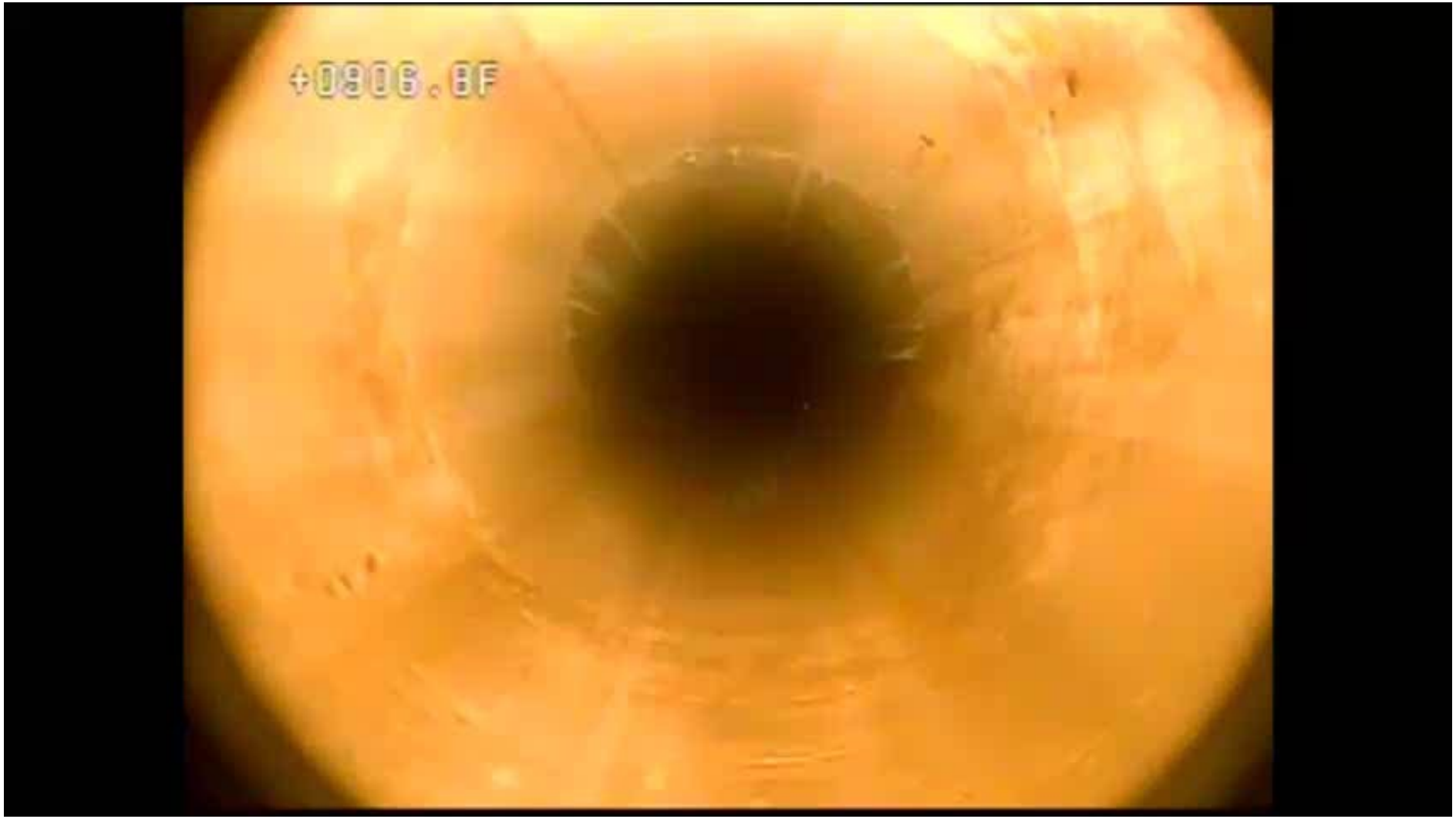
Cascading water above water level in the strat test hole

Outflow Zone

USGS

Outflow at 660 feet in *strat* test hole

Saline-Water Zone



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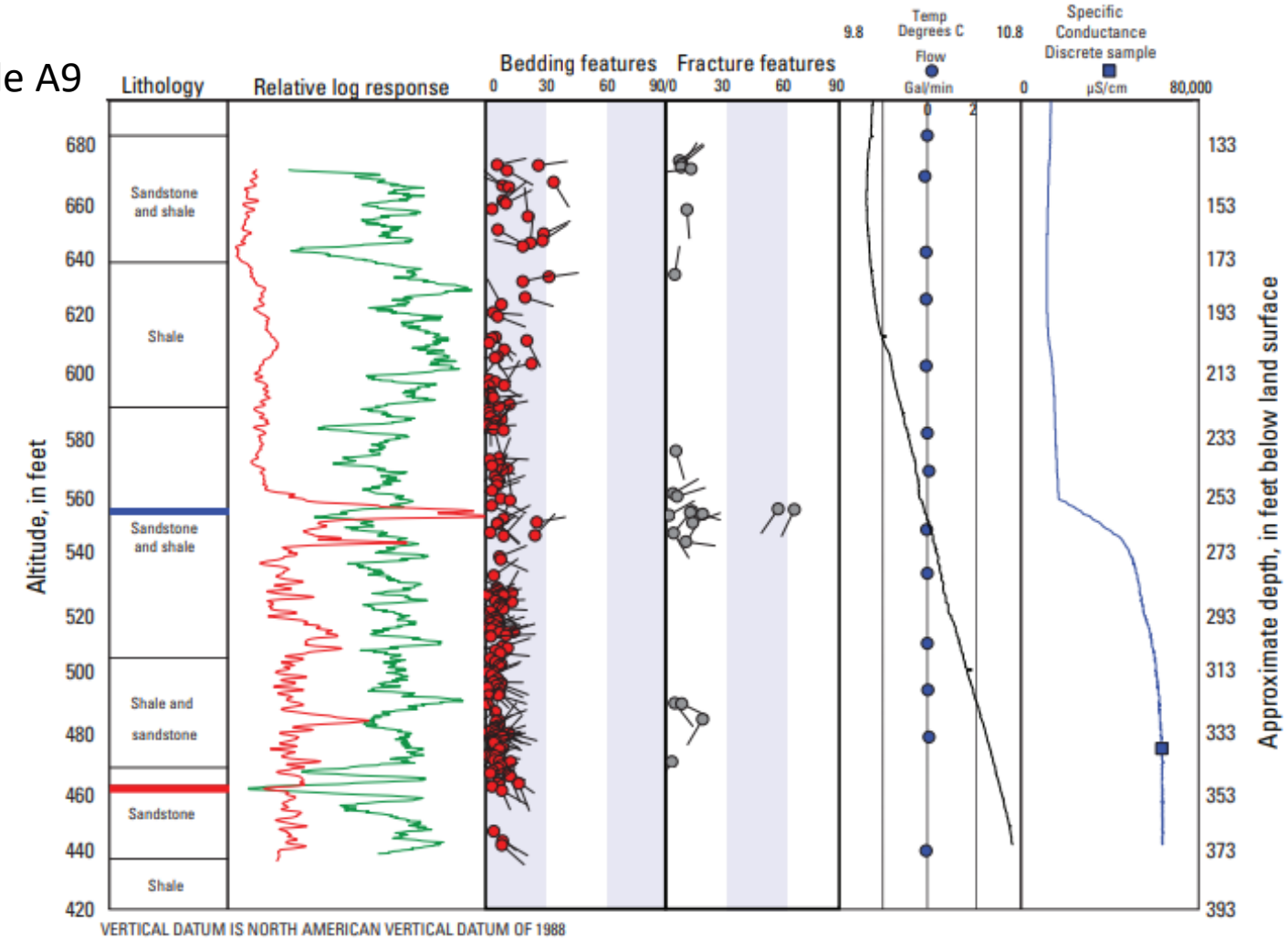
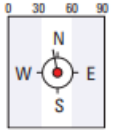
Saline-water zone at 915 feet in strat test hole

Borehole A9



EXPLANATION



Planar feature delineated on optical televiewer (OTV) and acoustic televiewer (ATV) logs; red "tadpole" indicates bedding and gray "tadpole" indicates fracture; "body" of tadpole indicates dip angle in degrees, and "tail" indicates the dip (azimuth) in degrees relative to True Geographic North

Water- and Gas-bearing zones

- Fresh water-bearing fractured zone
- Saline water-bearing fractured zone
- Gas-bearing zone (?)

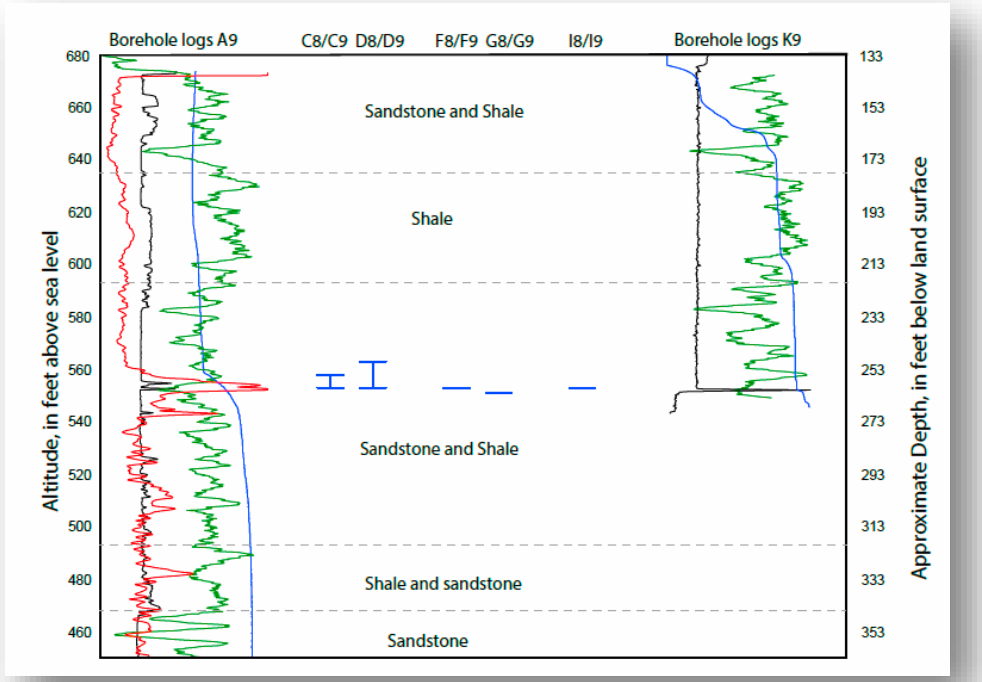
Geophysical log types

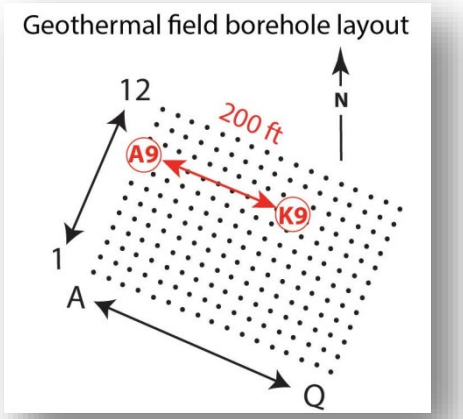
- Specific conductance
- Electromagnetic conductivity
- Gamma
- Water temperature

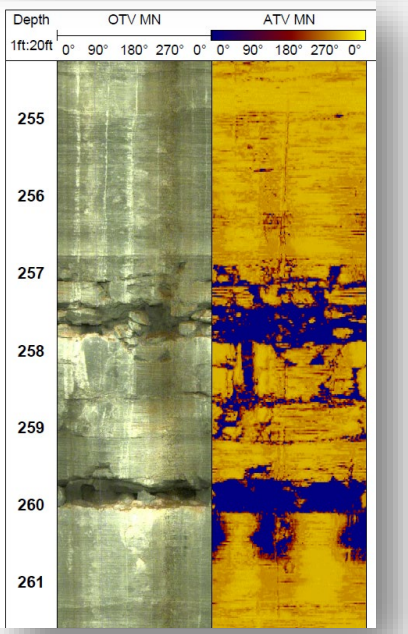
- **Flow, positive values indicate upward flow**
- **Specific conductance discrete sample**

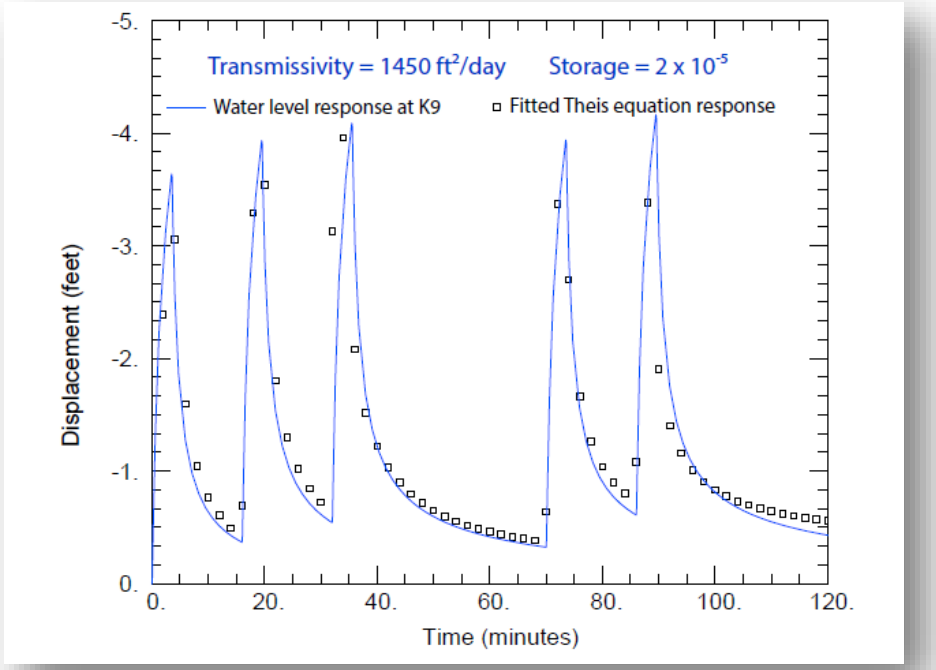
USGS

Saline-water bearing fractured zone in Allegheny Plateau geothermal borehole









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Methane gas unloading of borehole Q1
Discharged ~100 gal/min of saline water for 15 minutes

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https://pubs.usgs.gov/sir/2015/5155/sir20155155_appendix04.mp4


USGS
science for a changing world

Methane gas unloading of domestic water well west of Ballston Spa

Questions

- What would the responses be in gamma, normal resistivity, and EM conductivity logs to a saline water-bearing fractured zone in a well-cemented quartz sandstone?
- How would a dipping planar fracture appear on an acoustic televiewer log?
- What is the relation between borehole deviation and bedrock fabric (foliation, banding, bedding)
- What conditions result in groundwater being discharged to land surface from a borehole with no pumping?

USGS

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