BOREHOLE GEOPHYSICAL LOGGING

Applications for Environmental Site Remediation

Presented by

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OUTLINE

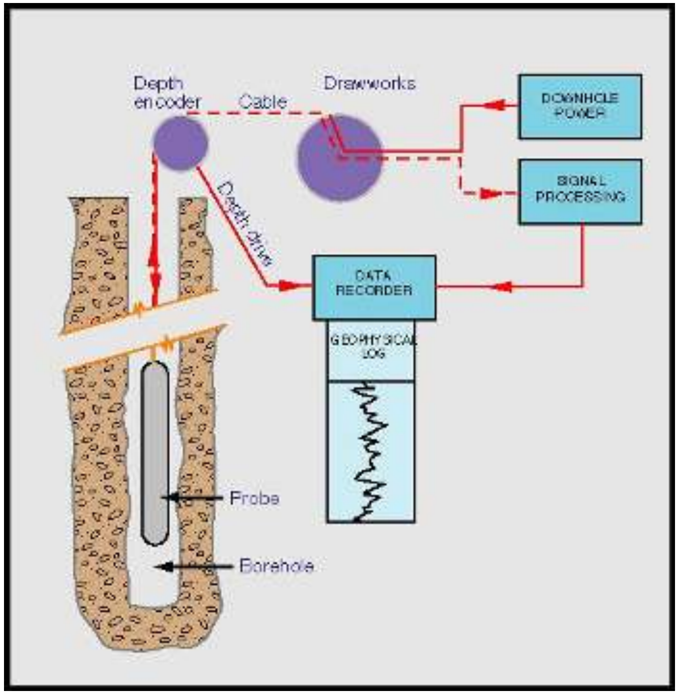
- What is borehole geophysical logging?
- Which important environmental site remediation problems can it help us solve?
- How is it used to do so?

Definition

Borehole Geophysics

- "methods for making continuous or point measurements down a drill hole… lowering different types of probes into borehole and electrically transmitting data to the surface where recorded… as a function of depth.
- "measurements related to the physical and chemical properties of the rocks surrounding the borehole and the fluid in the borehole, to the construction of the well, or to some combination of these factors."

(Keys, 1997)

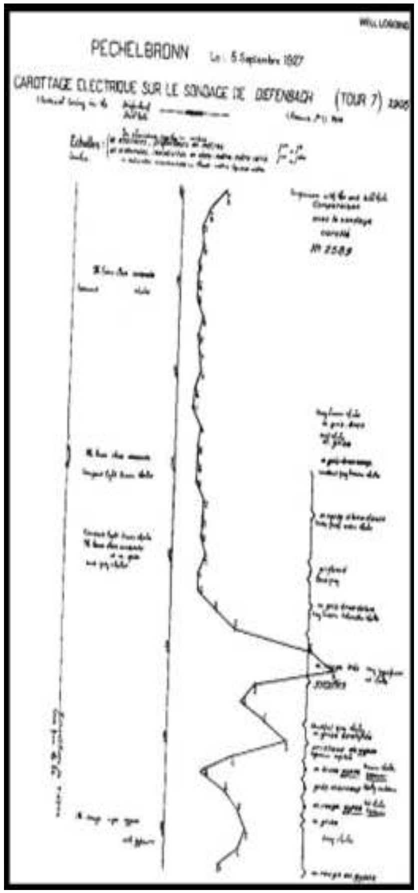


History

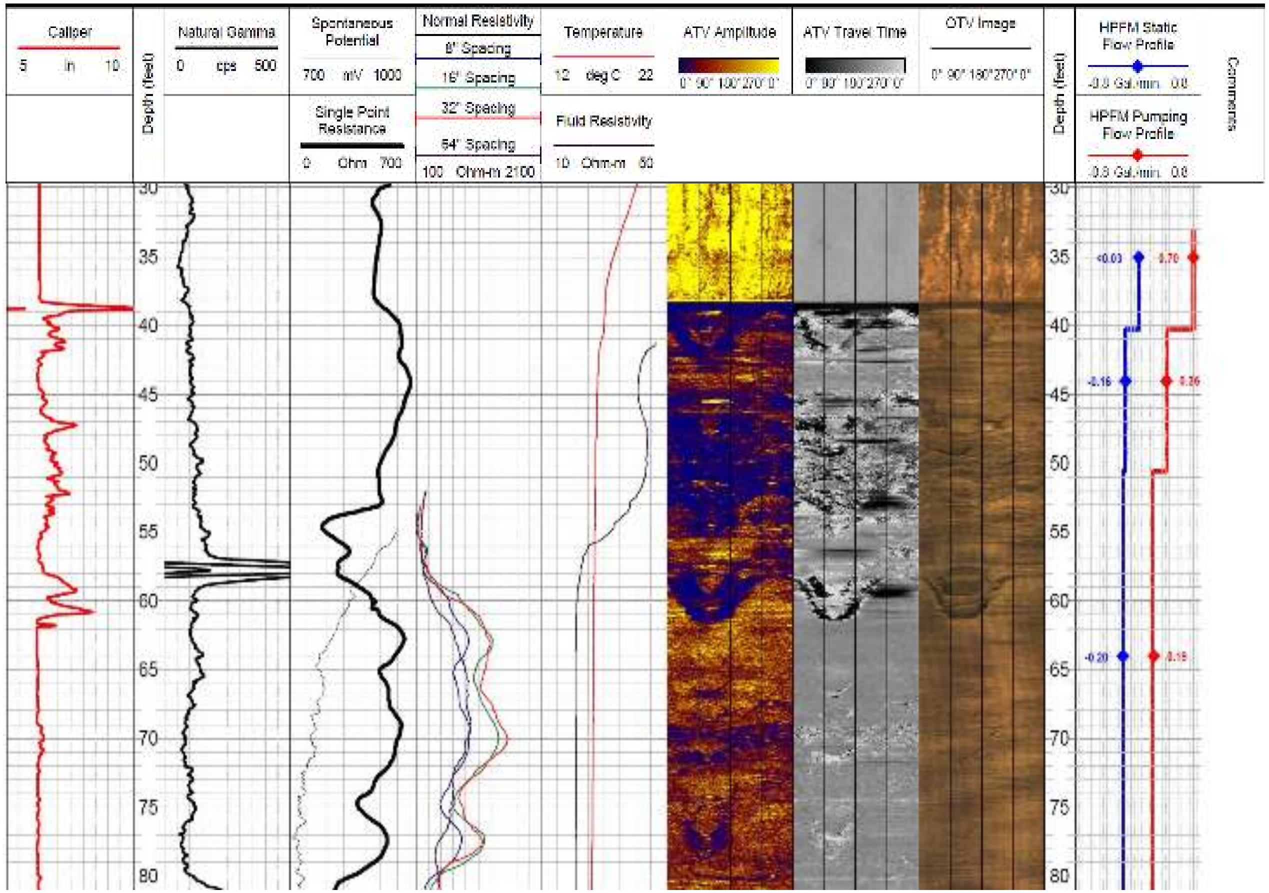
- First well log: 1927 by Schlumberger brothers (electrical resistivity) in France
- Additional electrical, nuclear, sonic, imaging and physical techniques developed for oil and gas, mineral exploration
- Adopted for use in water supply, geotechnical and environmental industries

History

Well Log - 1937



Modern Well Log



General Applicability

- Methods Available to Assess
  - Bedrock and Unconsolidated Formations
  - Open Boreholes or Completed Wells
  - Through Steel or PVC Casing

- Conceptual Site Model (CSM) Development and Refinement
- Investigative or Corrective Action
- Qualitatively or Quantitatively
- Support Design or Verify Performance

Pros and Cons

Benefits

- Continuous record
- Objective, numerical data
- Repeatable
- New info from existing wells
- Low cost, relative to other methods (e.g., coring)

Limitations / Qualifications

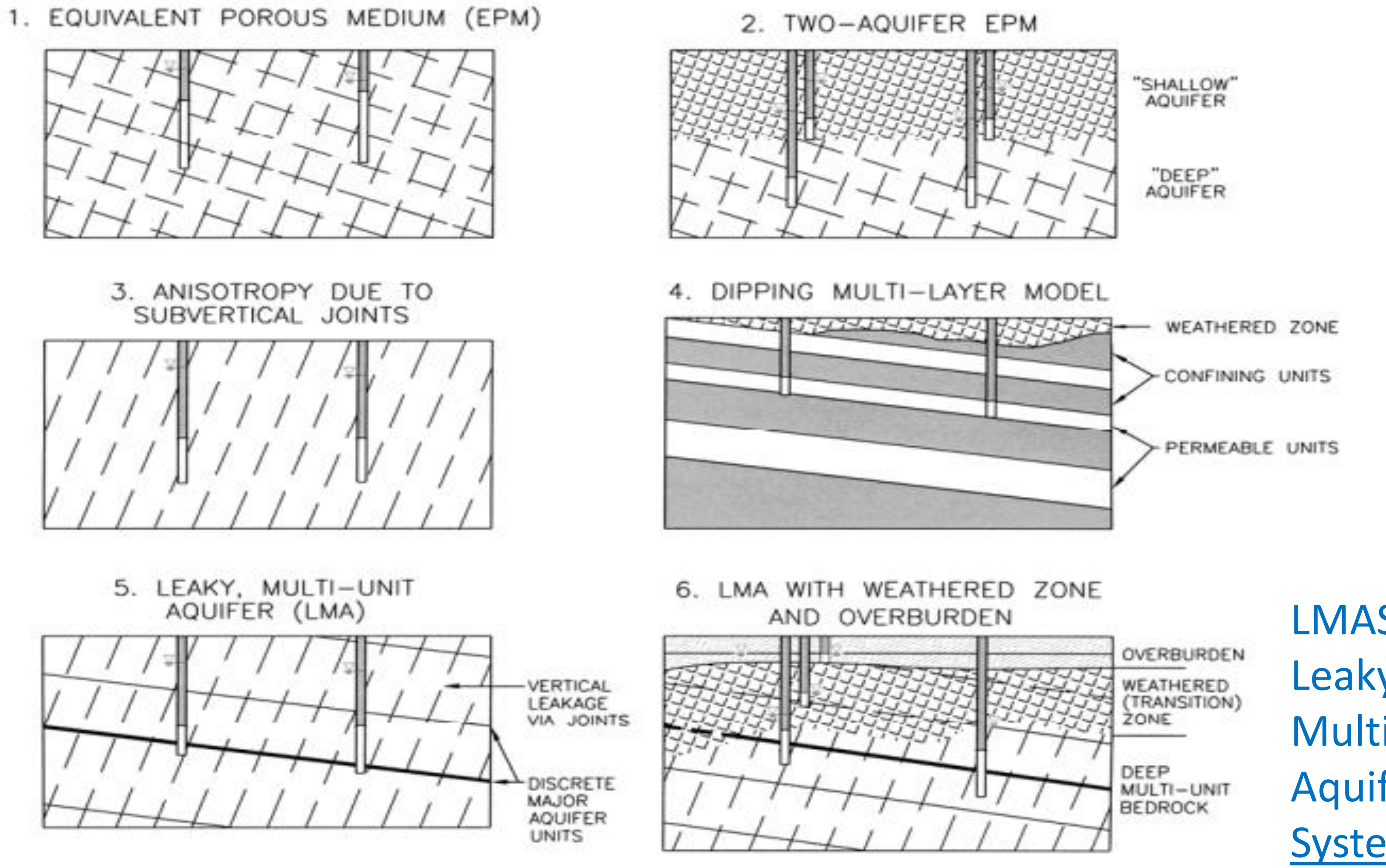
- Best applied with background information to aid in analysis, (e.g., soil or rock core data)
- Single logging parameter rarely diagnostic; synergistic analysis necessary
- Log interpretation requires experience, knowledge of regional hydrogeology

Sedimentary Bedrock – Examples at Outcrop

Questions

- Based on the photos shown, does it look like groundwater in sedimentary rock can be transmitted with equal ease in all directions?
- If not, which are the most obvious features which might give rise to extensive preferential conduits for flow?
- How many NJ/NY/PA industrial sites have beautiful rock exposures like these?

Conceptual Site Models – Dipping Sedimentary Bedrock

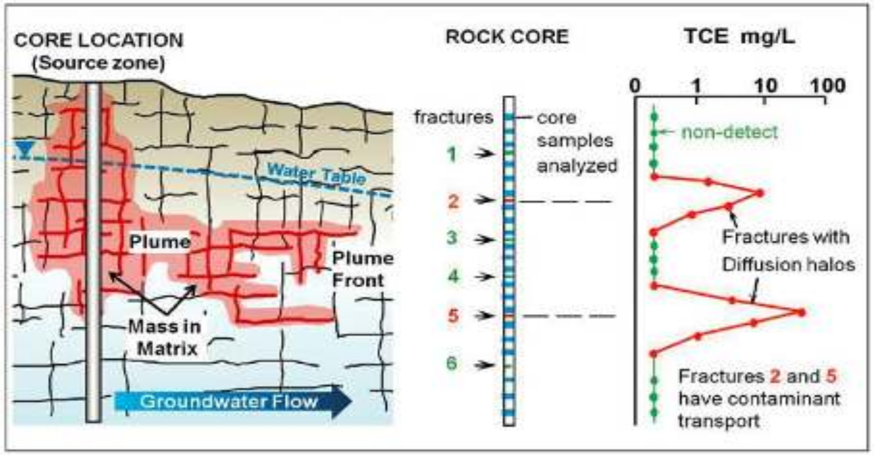


LMAS: Leaky, Multi-Unit Aquifer System

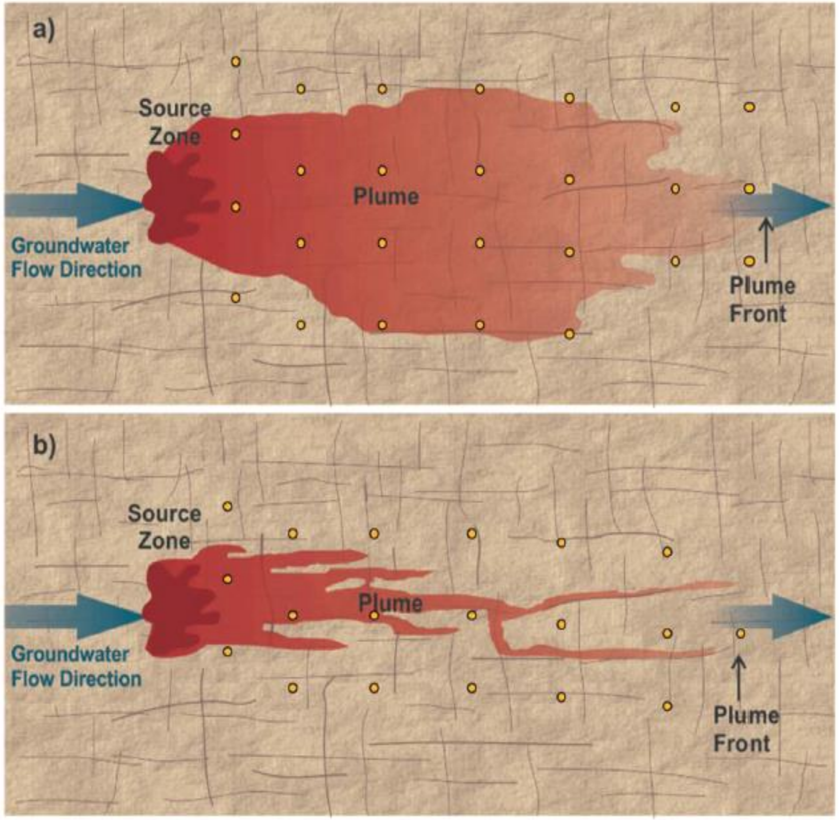
(Michalski, 2010 after Michalski and Britton, 1997)

Conceptual Site Models – Dipping Sedimentary Bedrock (cont’d)

Discrete Fracture Network



Effective Monitoring?

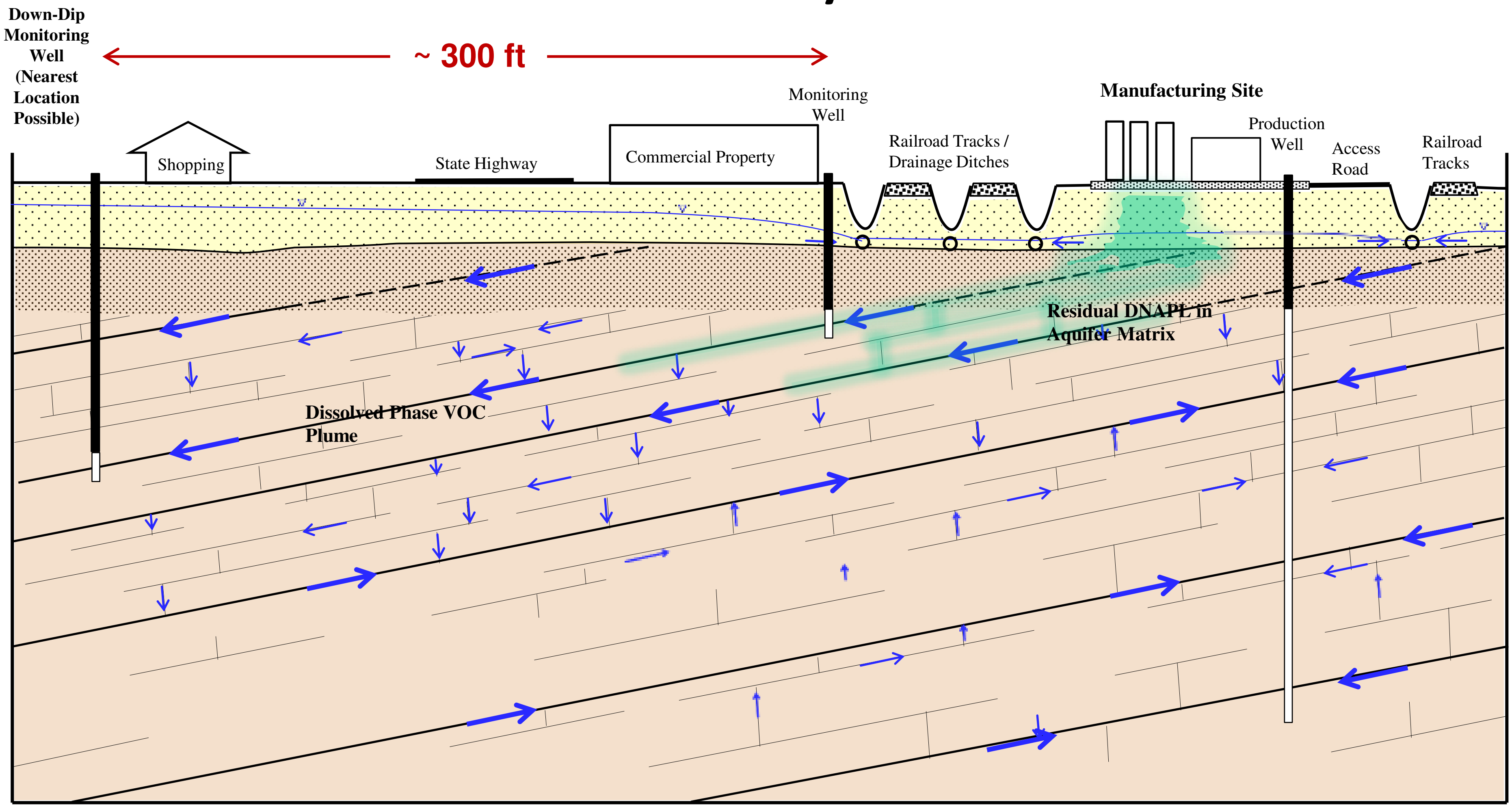


(Parker et al., 2012)

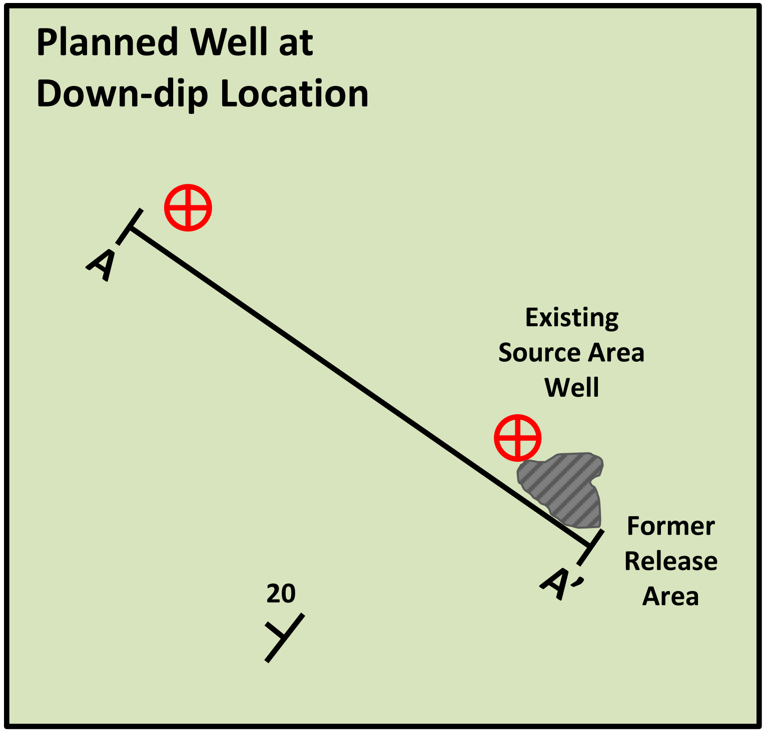
Monitoring Challenges – Dipping Sedimentary Bedrock

- Structure and Extent of Units - How Accurate?
- Flow and Plume Configuration within Units
- Representative and Efficient Monitoring

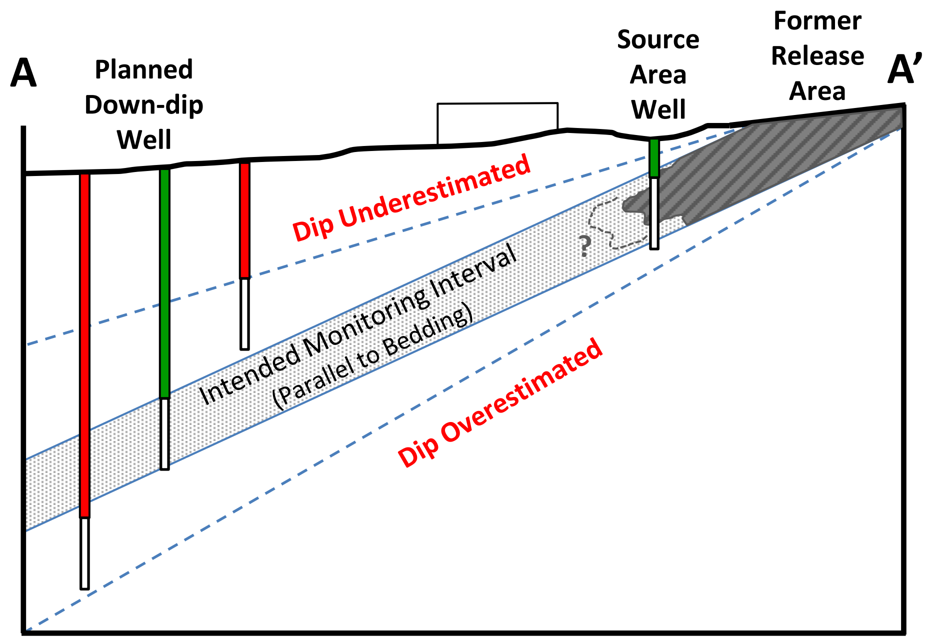
Monitoring Challenges – Dipping Sedimentary Bedrock



Planar Feature Orientation – Implications for Monitoring Accuracy



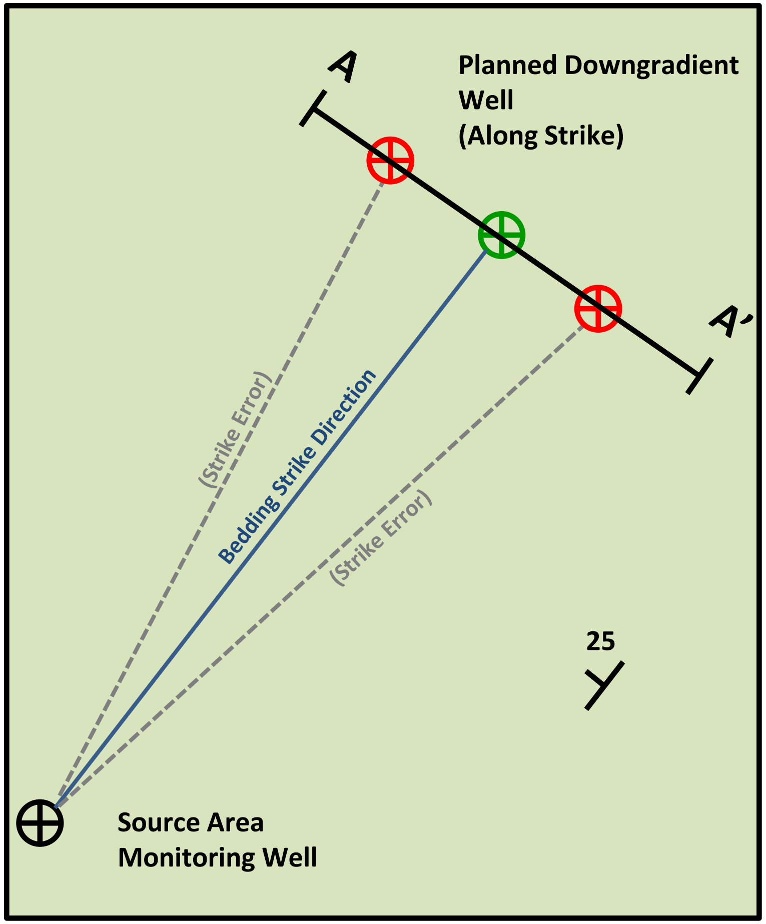
Dip Error Leads to Vertical Displacement – Missing the Intended Monitoring Zone



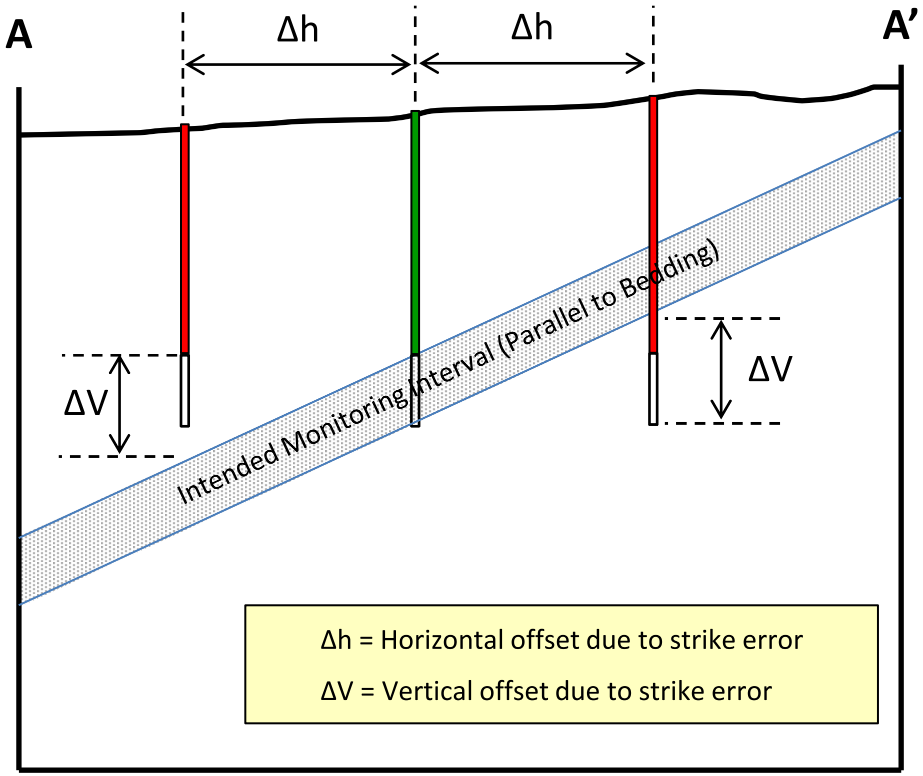
Planar Feature Orientation – Implications for Monitoring Accuracy

Dip Angle (degrees)	Error in Dip Angle (degrees)	Map Distance Parallel to Dip (ft) / Corresponding Vertical Error (ft) in Expected Elevation of Planar Feature			
		100	300	500	1000
15	0.2	0.4	1.1	1.9	3.7
	0.4	0.7	2.2	3.7	7.5
	0.6	1.1	3.4	5.6	11.3
	0.8	1.5	4.5	7.5	15.0
	1.0	1.9	5.6	9.4	18.8
	3.0	5.7	17.1	28.5	57.0
	5.0	9.6	28.8	48.0	96.0

Planar Feature Orientation – Implications for Monitoring Accuracy



Strike Error Leads to Vertical Displacement – Missing the Intended Monitoring Zone

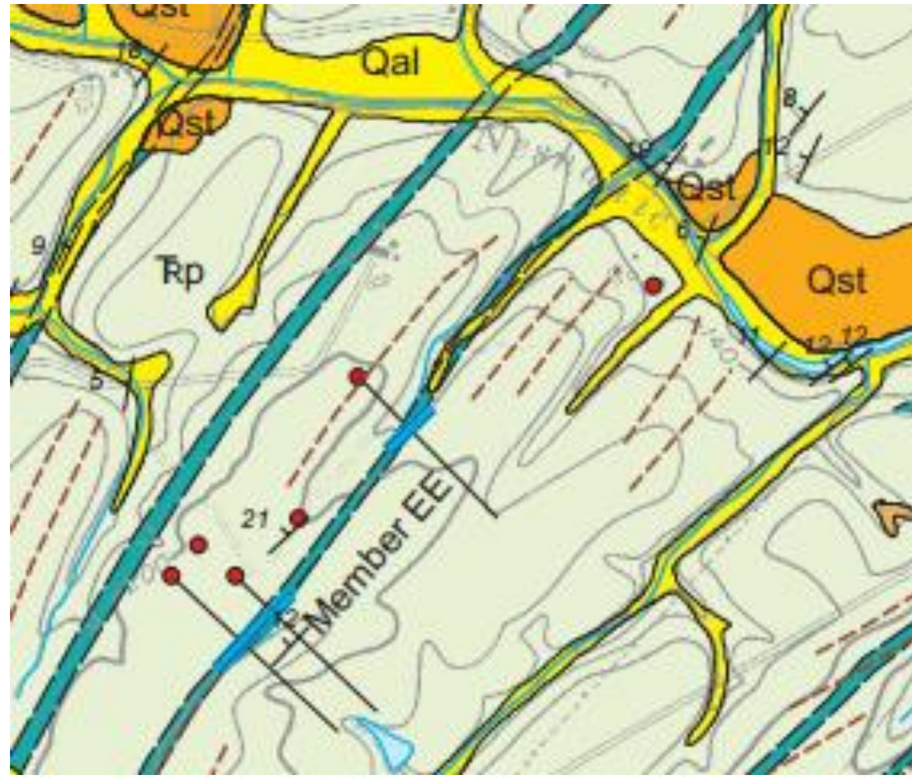


Planar Feature Orientation – Implications for Monitoring Accuracy

Error in Strike Angle (degrees)	Map Distance Along Assumed Strike (ft) / Corresponding Horizontal Error Perpendicular to Strike (ft) and Vertical Error in Expected Elevation of Planar Feature (ft) at Dip Angles of 10, 15, 20 and 25 Degrees																			
	100					300					500					1000				
	Hz Error	Dip, Resulting Vertical Error				Hz Error	Dip, Resulting Vertical Error				Hz Error	Dip, Resulting Vertical Error				Hz Error	Dip, Resulting Vertical Error			
		10	15	20	25		10	15	20	25		10	15	20	25		10	15	20	25
1.0	1.7	0.3	0.5	0.6	0.8	5.2	0.9	1.4	1.9	2.4	8.7	1.5	2.3	3.2	4.1	17.5	3.1	4.7	6.4	8.1
2.0	3.5	0.6	0.9	1.3	1.6	10.5	1.8	2.8	3.8	4.9	17.5	3.1	4.7	6.4	8.1	34.9	6.2	9.4	12.7	16.3
3.0	5.2	0.9	1.4	1.9	2.4	15.7	2.8	4.2	5.7	7.3	26.2	4.6	7.0	9.5	12.2	52.4	9.2	14.0	19.1	24.4
4.0	7.0	1.2	1.9	2.5	3.3	21.0	3.7	5.6	7.6	9.8	35.0	6.2	9.4	12.7	16.3	69.9	12.3	18.7	25.5	32.6
5.0	8.7	1.5	2.3	3.2	4.1	26.2	4.6	7.0	9.6	12.2	43.7	7.7	11.7	15.9	20.4	87.5	15.4	23.4	31.8	40.8
6.0	10.5	1.9	2.8	3.8	4.9	31.5	5.6	8.4	11.5	14.7	52.6	9.3	14.1	19.1	24.5	105.1	18.5	28.2	38.3	49.0
7.0	12.3	2.2	3.3	4.5	5.7	36.8	6.5	9.9	13.4	17.2	61.4	10.8	16.5	22.3	28.6	122.8	21.7	32.9	44.7	57.3
8.0	14.1	2.5	3.8	5.1	6.6	42.2	7.4	11.3	15.3	19.7	70.3	12.4	18.8	25.6	32.8	140.5	24.8	37.7	51.2	65.5
9.0	15.8	2.8	4.2	5.8	7.4	47.5	8.4	12.7	17.3	22.2	79.2	14.0	21.2	28.8	36.9	158.4	27.9	42.4	57.6	73.9
10.0	17.6	3.1	4.7	6.4	8.2	52.9	9.3	14.2	19.3	24.7	88.2	15.5	23.6	32.1	41.1	176.3	31.1	47.2	64.2	82.2

Bedding Attitude from Quad Maps?

- Local measurements of strike and dip vary widely relative to area-wide value needed for monitoring
- Strike ridge and Member plots meant to suggest larger scale – but mostly inferred

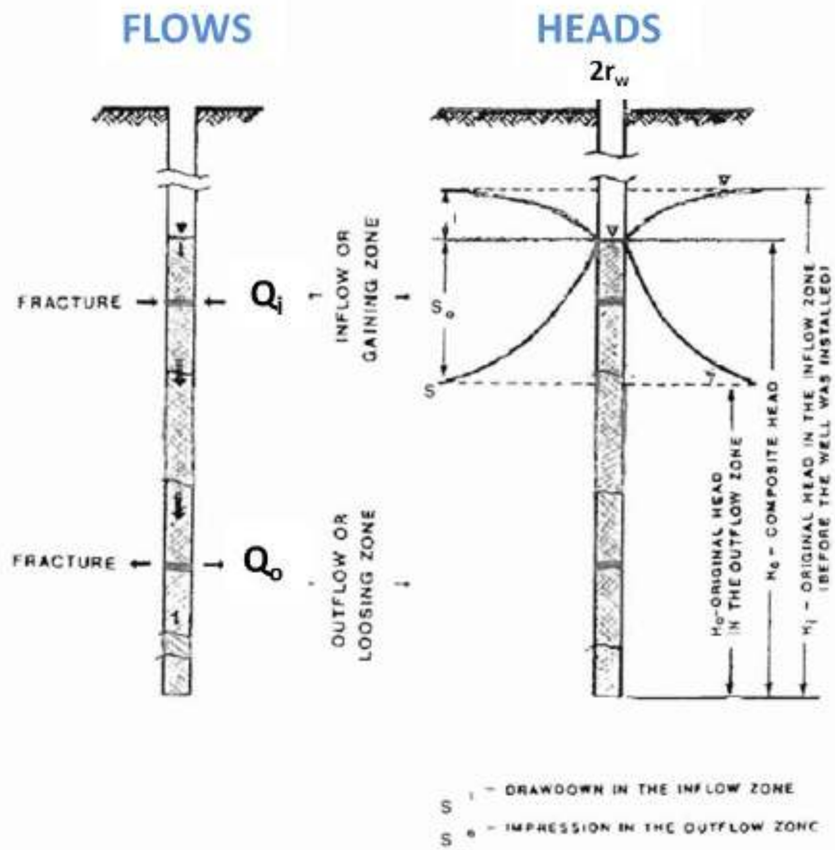


Downhole Optical Televiewer interpretation. Shows marker beds identified in borehole projected to land surface using bed orientation identified in well. In igneous rocks, shows orientation of flow structures. Red dot shows well location. Data from Herman and Curran (2010a, 2010b).

Strike ridge - ridge or scarp parallel to strike of bedrock. Mapped from stereo airphotos.

(Monteverde et al., 2014)

Cross-Flow Hydraulics of Multi-aquifer Wells



Simple Case: 1 inflow, 1 outflow

$$Q_{IN} = Q_{OUT}$$

$$s_i = H_i - H_c$$

$$s_o = H_o - H_c$$

$$Q_i = \frac{2\pi T_i s_i}{\ln\left(\frac{R}{r_w}\right)} \qquad Q_o = \frac{2\pi T_o s_o}{\ln\left(\frac{R}{r_w}\right)}$$

$$H_c = \frac{H_i T_i + H_o T_o}{T_i + T_o}$$

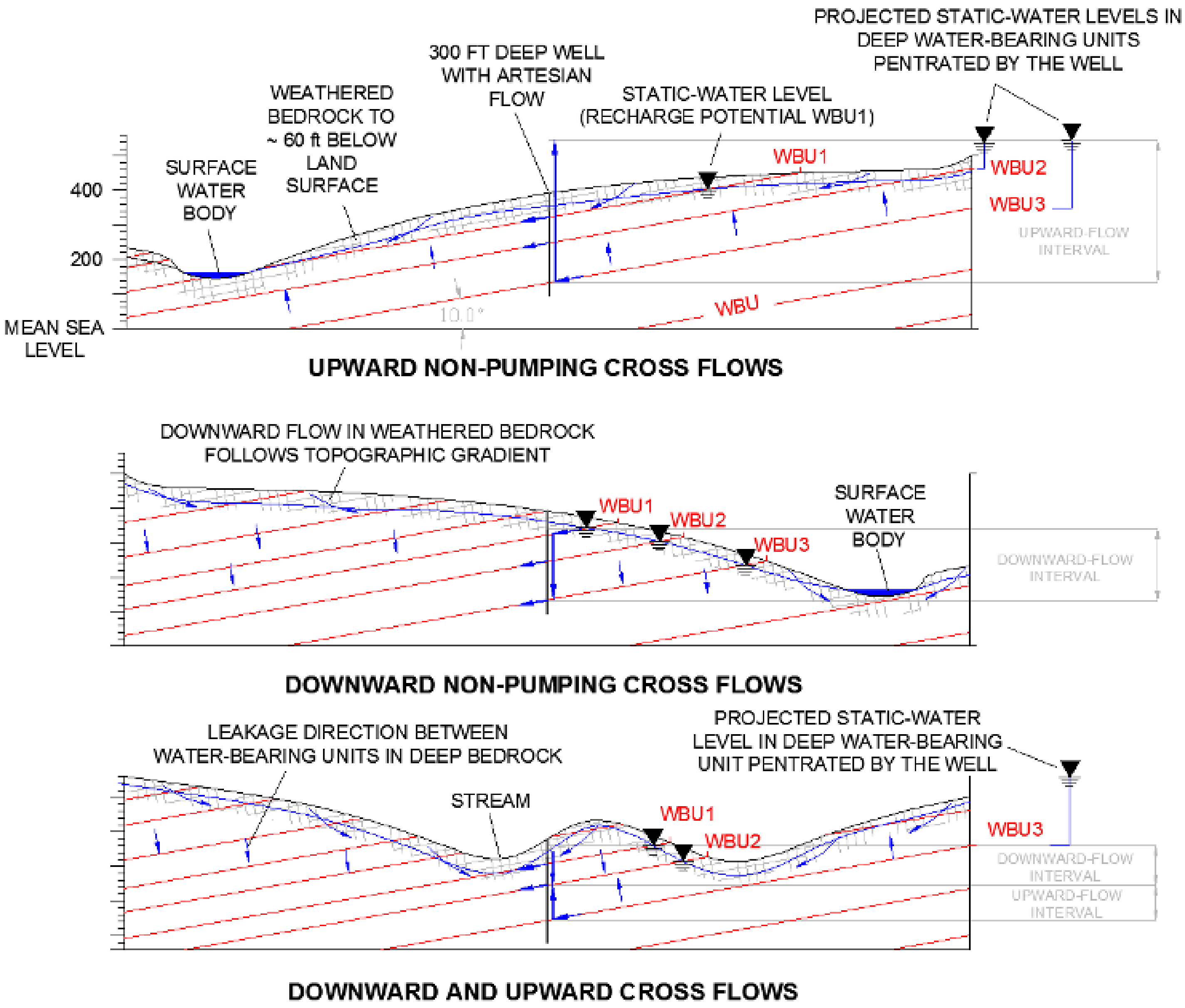
$$\frac{s_i}{s_o} = \frac{T_o}{T_i}$$

General Case: 3+ zones

$$H_c = \frac{T_1 H_1 + T_2 H_2 + \cdots + TnHn}{T_1 + T_2 + \cdots + Tn}$$

(Sokol 1963; Michalski and Klepp 1990)

Complex, but Systematic Flow in Bedrock



(Herman 2010)

Unconsolidated Formations – Potential CSM Complexity

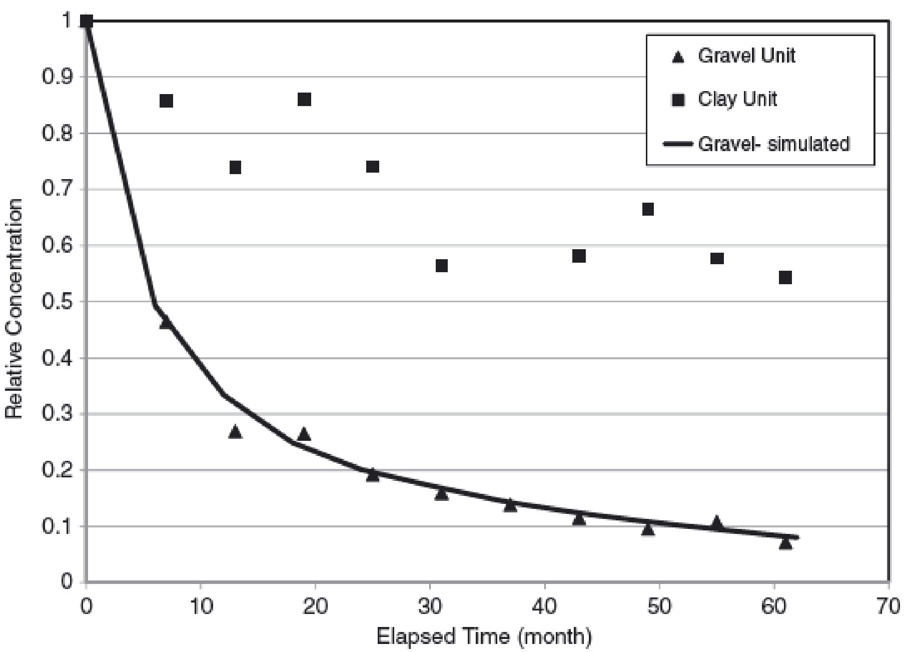
- Hydrostratigraphy
  - Confining Unit Lateral Extent
  - Hydrostratigraphic Unit Definition and Delineation
  - Anomalous Water Levels, Chemistry
- Previously Unidentified Low-K Lenses may Function as:
  - Contaminant Sinks (Diffusion)
  - Contaminant Sources (Back-Diffusion)

Unconsolidated Formations – Potential CSM Complexity (cont'd)


Monitoring&Remediation

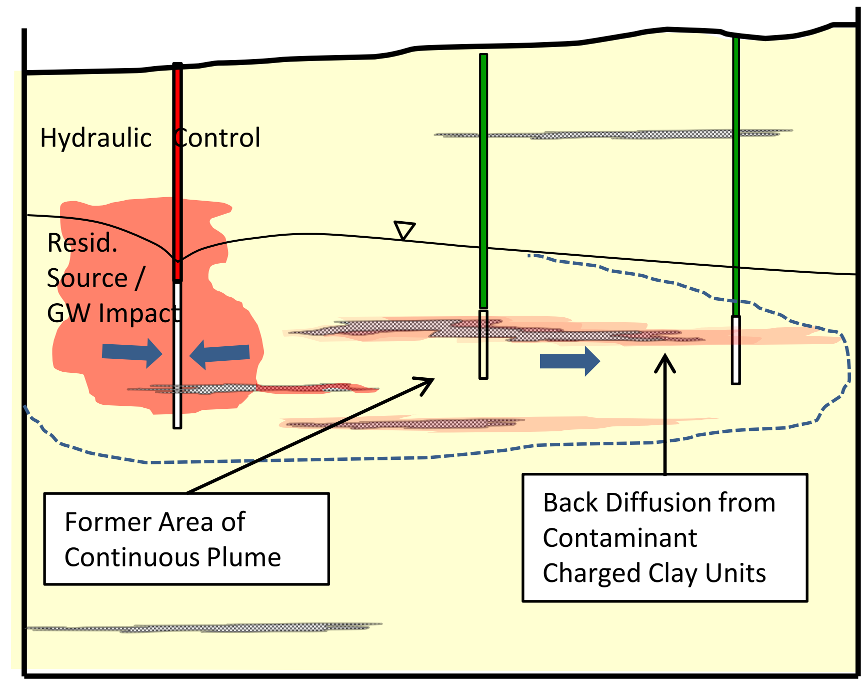
Persistence of a Groundwater Contaminant Plume after Hydraulic Source Containment at a Chlorinated-Solvent Contaminated Site

by D. E. Matthieu III, M. L. Brusseau, Z. Guo, M. Plaschke, K. C. Carroll, and F. Brinker



(Matthieu, Brusseau et al. 2014)

Contaminant Back Diffusion from Clays causing Persistent, Low-Level Impact in Former Plume Area after Source Remedy

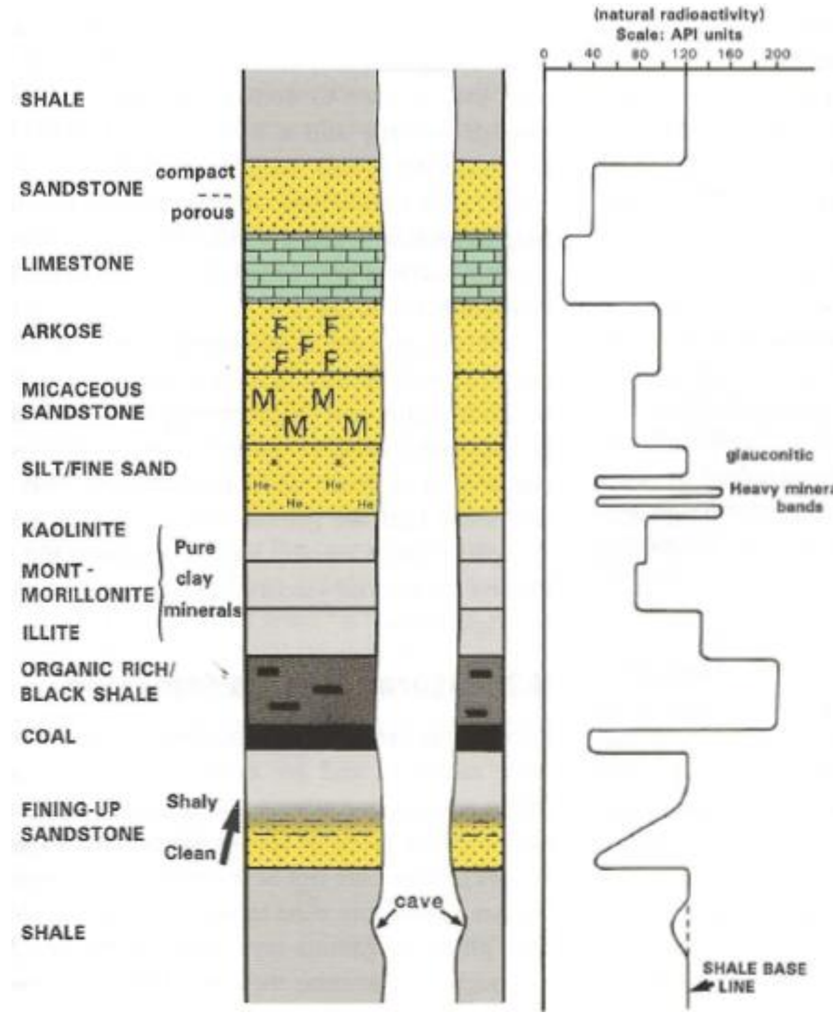


Geophysical Logging Methods / Applications

LOG TYPES	PRIMARY USES	OTHER USE(S)
Natural Gamma	Hydrostratigraphy, lithologic correlation, area-wide structure	Natural radioactivity
Electrical Logs; EM Induction	Hydrostratigraphy, lithologic correlation, area-wide structure	Water quality; conductive mineral content; estimate porosity
Caliper	Assess hole or well condition, ID fractures	Infer lithology, contacts
Fluid Logs	ID ambient vertical cross-flows and the fractures or zones between which such exchange takes place	Assess water quality at inflow zones (estimate TDS)
Image Logs	ID and determine structural attitude of planar features (bedding, foliation, fractures); lithology and structure near borehole; visual inspection	ATV: Acoustic caliper; PVC casing/ cement inspection; steel casing corrosion loss; annular volume log to plan well construction/abandonment
Flow Logs	Quantify direction and magnitude of ambient cross-flows; determine hydraulic heads and Transmissivities for each hydraulically active fracture or zone while pumping	Multi-well testing to assess and quantify hydraulic connections between wells
Water Quality	Depth-discrete grab sampling at inflow zones; vertical profiling of water quality / redox indicator parameters	Cross-contamination assessment and mitigation planning

Natural Gamma

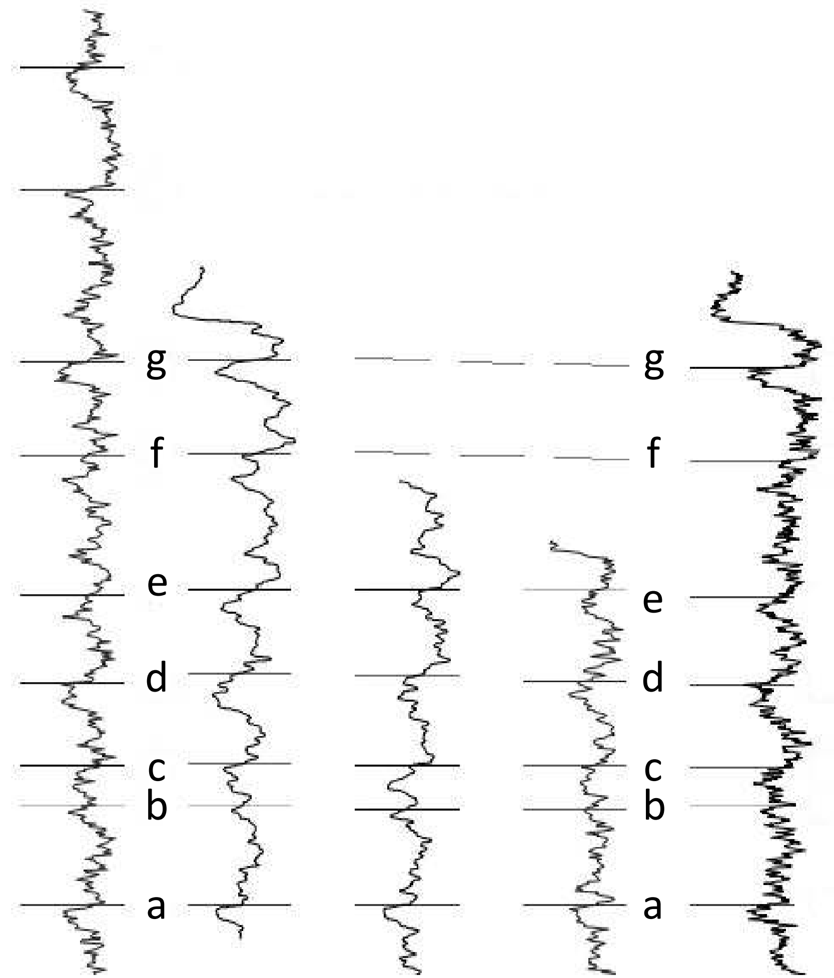
- Records Gamma Rays Emitted by Materials Adjacent to Hole
- Used in:
  - Open Holes or Completed Wells
  - Through Steel or PVC Casing
- Gamma from U, K-40 and Th, Abundant in and Adsorbed to Clays
- Sometimes Called "Shale Log"
- Misnomer: <u>K-feldspar Rich Sands</u> also Have High Gamma



(Rider and Kennedy 2011)

Correlating Gamma Logs to Define Stratigraphic Markers

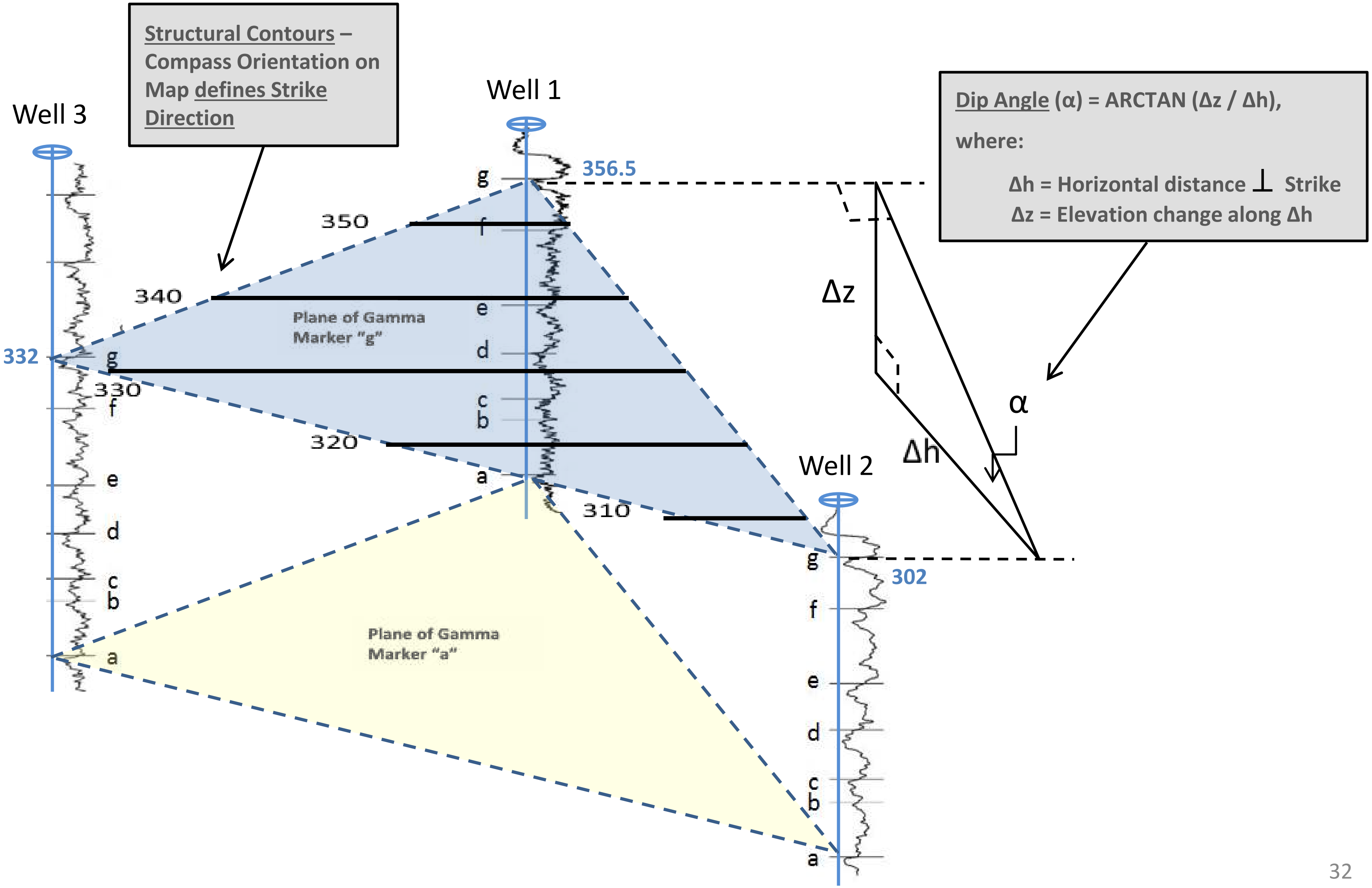
- Used for:
  - Interpreting Lithology
  - Gamma Markers Common to 3 or More Locations Support Determination of Bedding Strike and Dip
  - Natural Radioactivity



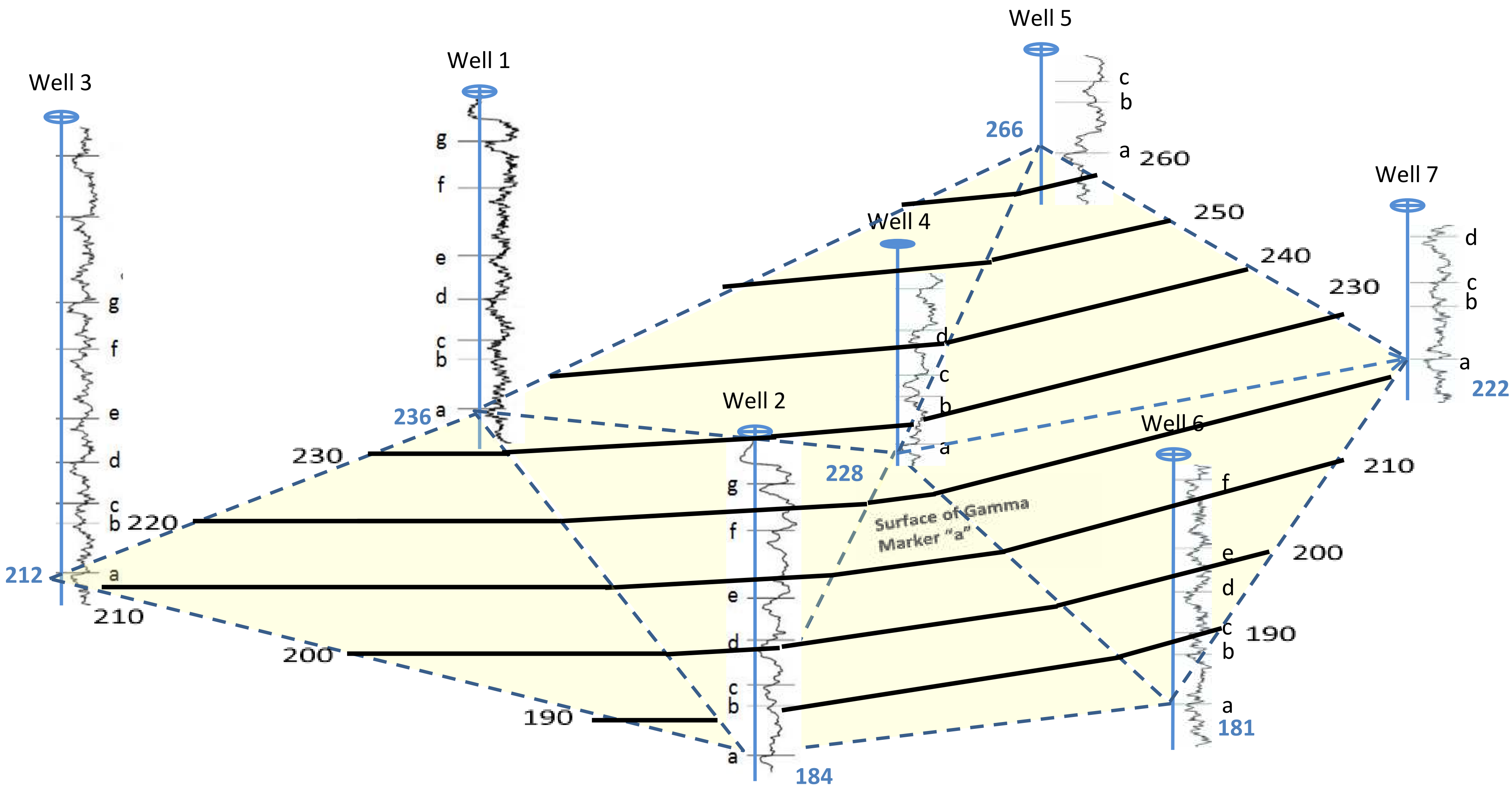
Verifying that Stratigraphic Markers are Laterally Continuous and Parallel

WELL ID		Well 1	Well 2	Well 3	Well 4	Well 5	House 1	House 2	Site-Wide Separation of Stratigraphic Markers	
WELL LOGGED BY		Princeton Geoscience	Princeton Geoscience	Princeton Geoscience	Princeton Geoscience	Princeton Geoscience	Company #2	Company #3		
DATE OF LOGGING		06/23/13	06/23/13	06/23/13	06/24/13	06/24/13	03/25/97	12/10/05	Mean Value	Standard Deviation
REFERENCE ELEVATIONS	PVC	304.47	299.55	265.72	287.34	264.47	*	*		
	RISER	304.79	299.73	265.89	287.58	264.66	270.64	293.66		
	GROUND	302.4	295.6	263.2	284.7	261.7	267.0	*292.6*		
LOGGING REFERENCE		PVC	PVC	PVC	PVC	PVC	RISER	RISER		
MARKERS INTERSECTED		a - f	c - f	a - f	d - f	c - e	b - f	a - f		
f	Depth	181.0	190.0	23.0	89.0		112.5	192.5		
	Elevation	123.5	109.6	242.7	198.3		158.1	101.2		
Separation		22.5	23.5	23.0	24.0		22.5	22.0	22.9	0.7
e	Depth	203.5	213.5	46.0	113.0	35.0	135.0	214.5		
	Elevation	101.0	86.1	219.7	174.3	229.5	135.6	79.2		
Separation		11.5	12.0	13.0	12.5	13.0	13.0	11.5	12.4	0.7
d	Depth	215.0	225.5	59.0	125.5	48.0	148.0	226.0		
	Elevation	89.5	74.1	206.7	161.8	216.5	122.6	67.7		
Separation		20.0	19.5	21.0		20.0	20.0	20.0	20.1	0.5
c	Depth	235.0	245.0	80.0		68.0	168.0	246.0		
	Elevation	69.5	54.6	185.7		196.5	102.6	47.7		
Separation		18.0		17.5			19.0	19.0	18.4	0.8
b	Depth	253.0		97.5			187.0	265.0		
	Elevation	51.5		168.2			83.6	28.7		
Separation		11.0		11.5				9.5	10.7	1.0
a	Depth	264.0		109.0				274.5		
	Elevation	40.5		156.7				19.2		

Strike and Dip using Gamma Markers

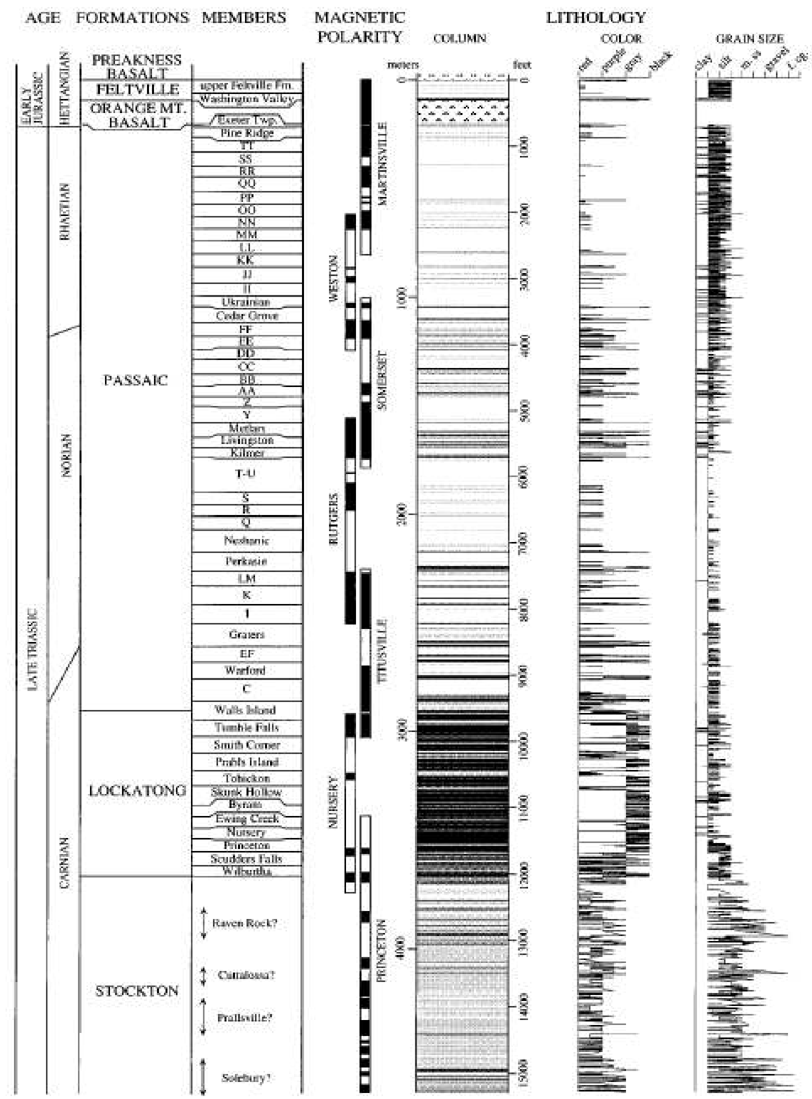


Multi-Point Solution to Confirm Planarity or Resolve Structure



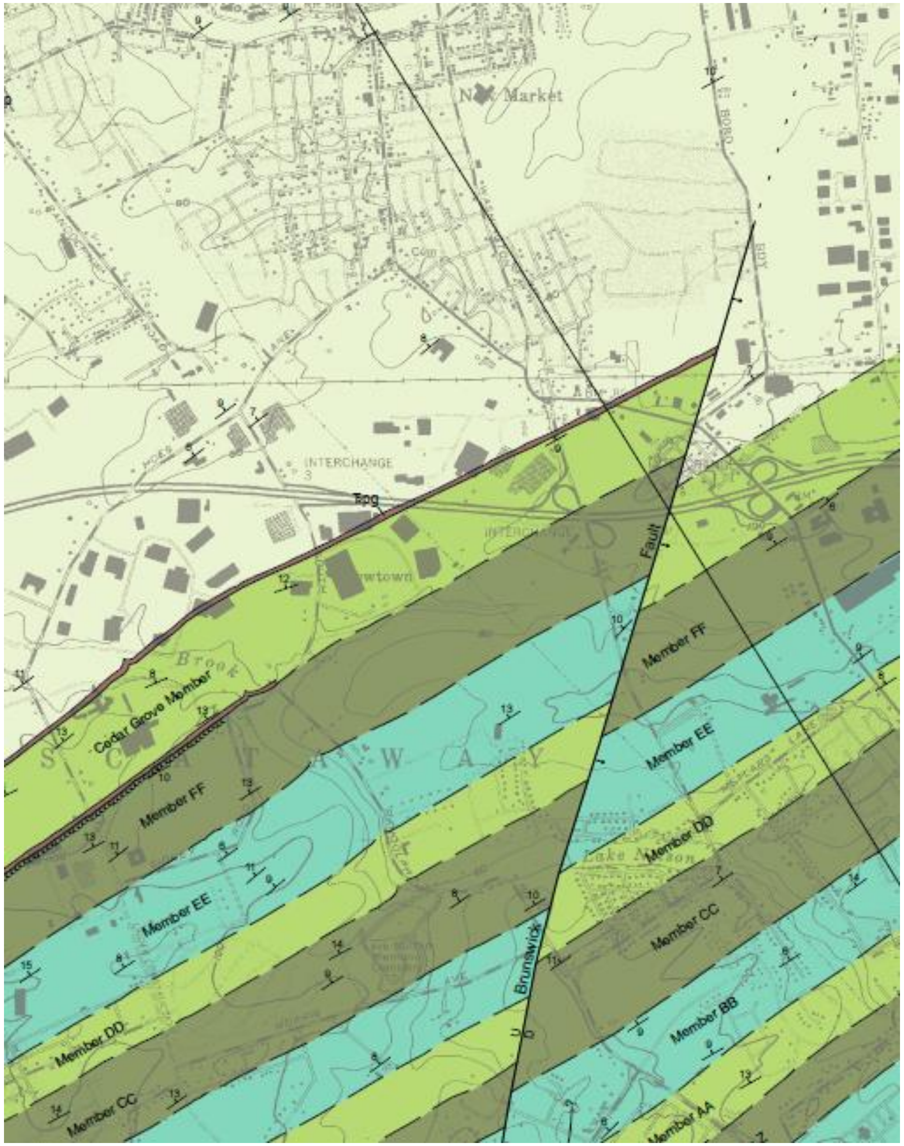
Gamma Correlation with Regional Units

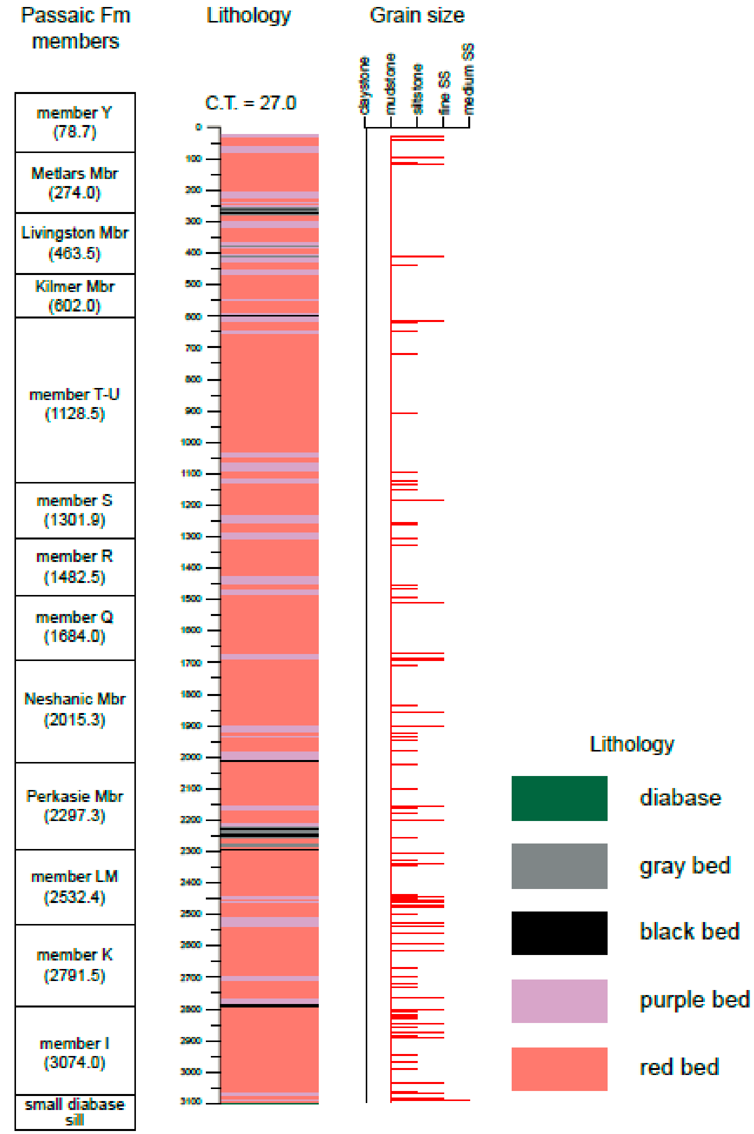
- Newark Basin Coring Project (NBCP)
  - Extensive geologic framework
  - Electronic data available for gamma logs, lithology, color
  - Many units correlate readily over large distances (miles)
- NJGS maps (e.g., Plainfield Quad) reflect NBCP sub-units
- Elements of CSM per USGS at NAWC research site in West Trenton (Lacombe and Burton 2010)
- Understanding gained may support focused approach



(Olsen, Kent et al. 1996)

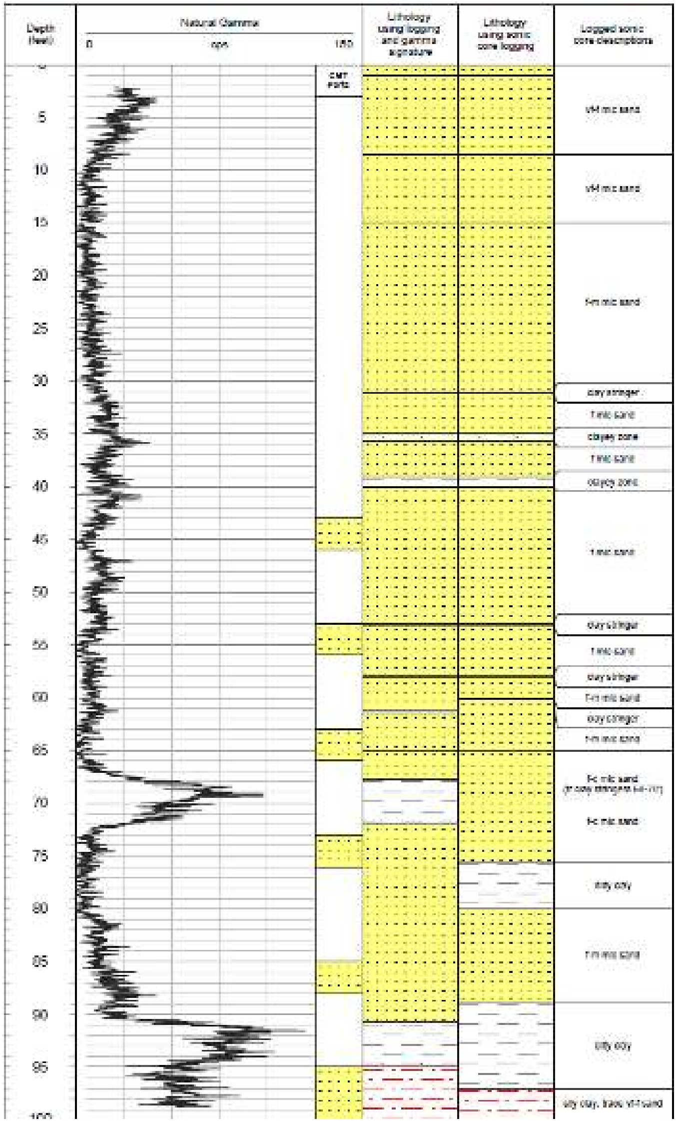
Mapping of Passaic Fm. Members





(Volkert et al., 2013)

Assigning Accurate Depths for Clays in Disturbed Cores – Gamma Log Enables CMT Placement



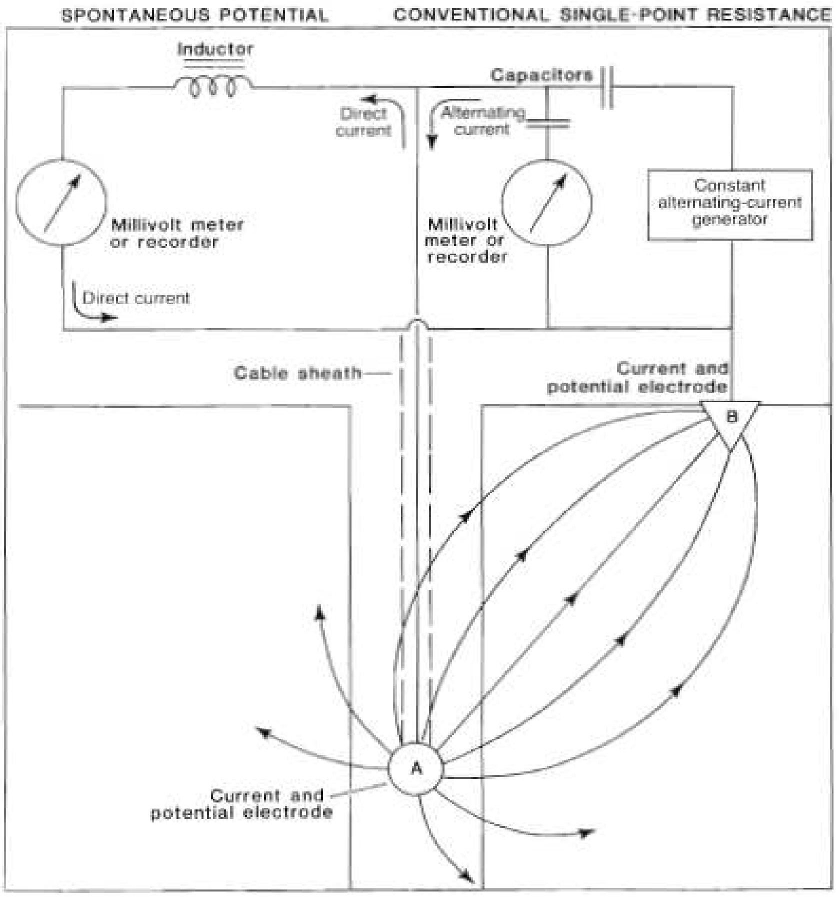
- When coring long intervals (20 ft with sonic), strata can be vertically displaced up to several feet in resulting core
- Gamma log to TD through sonic rods can establish bed boundaries of clays to w/in ~1 foot
- Enables assignment of soil sample depths and CMT® port/well screen placement with needed accuracy

Electrical Logs

- Based on Ohm's Law:

  Resistance (Ohms) = Potential (V) / Current (Amps)

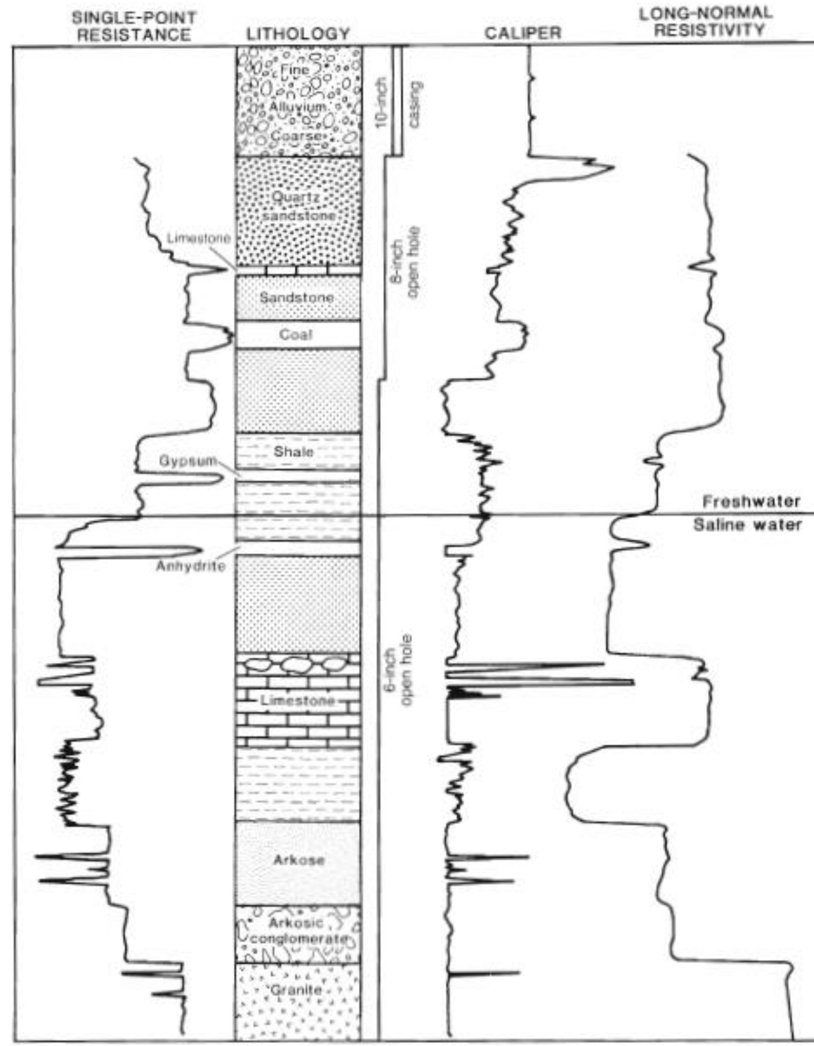
- Single Point Resistance (SPR), Spontaneous Potential (SP): Bulk measures between surface electrode and probe in borehole
- SP interpretation complex in fresh ground water



(Keys 1989)

Electrical Logs (cont'd)

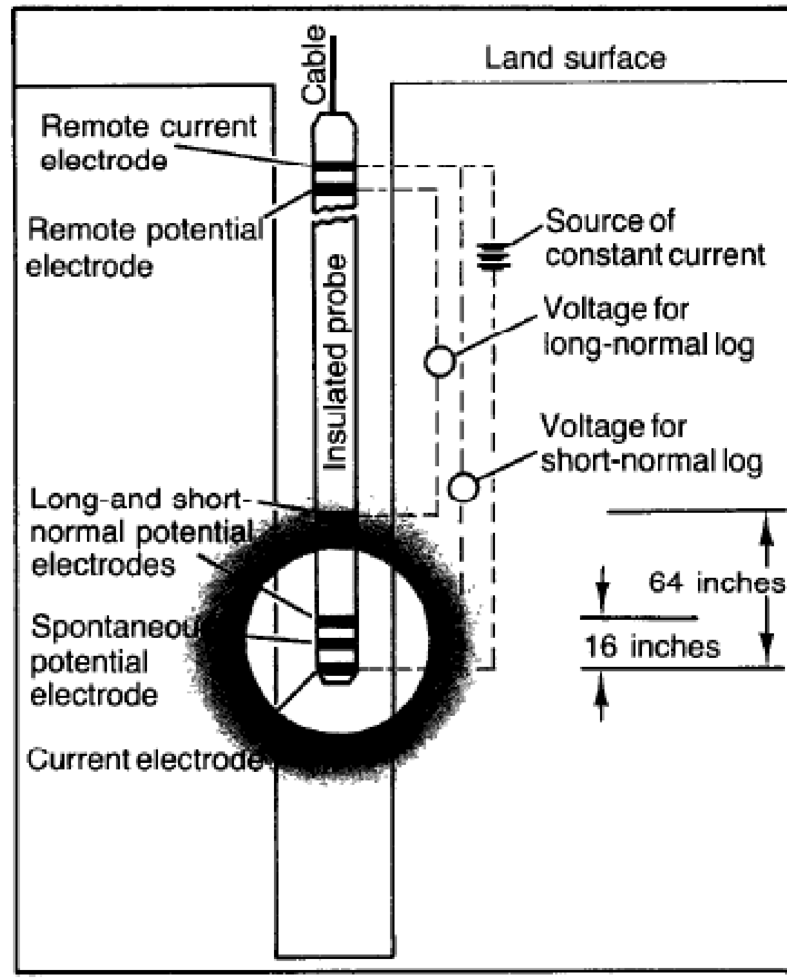
- SPR: Resistance to constant applied A/C current
- Indicated by voltage, calculated in Ohms
- Mostly affected by porosity and salinity of porewater
- Surface conduction on clays and conductive minerals play lesser role
- Support lithology and fracture ID



(Keys 1989)

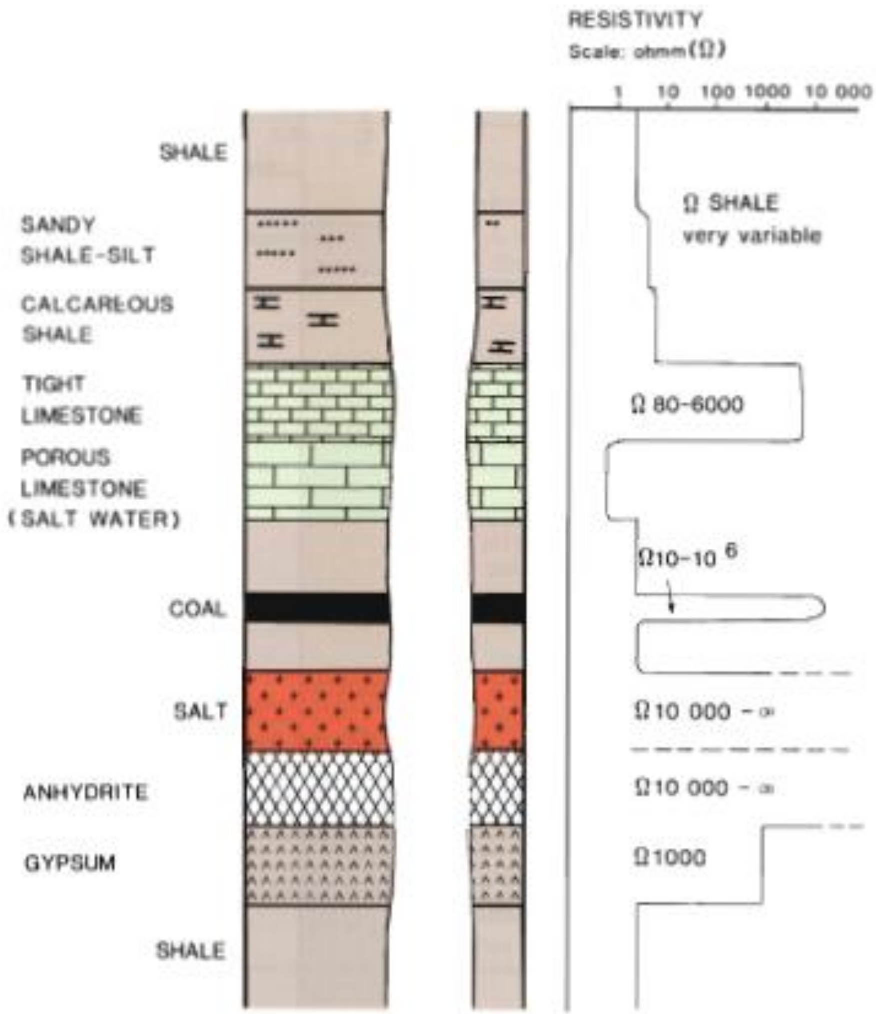
Electrical Logs (cont'd)

- Normal Resistivity: Intrinsic measure of rock or soil and pore fluids around borehole (in Ohm-Meters)
- Different electrode spacings vary depth of investigation
- Related mostly to porewater quality, moisture content, and porosity
- SPR and Normal Resistivity Complement Gamma for lithology

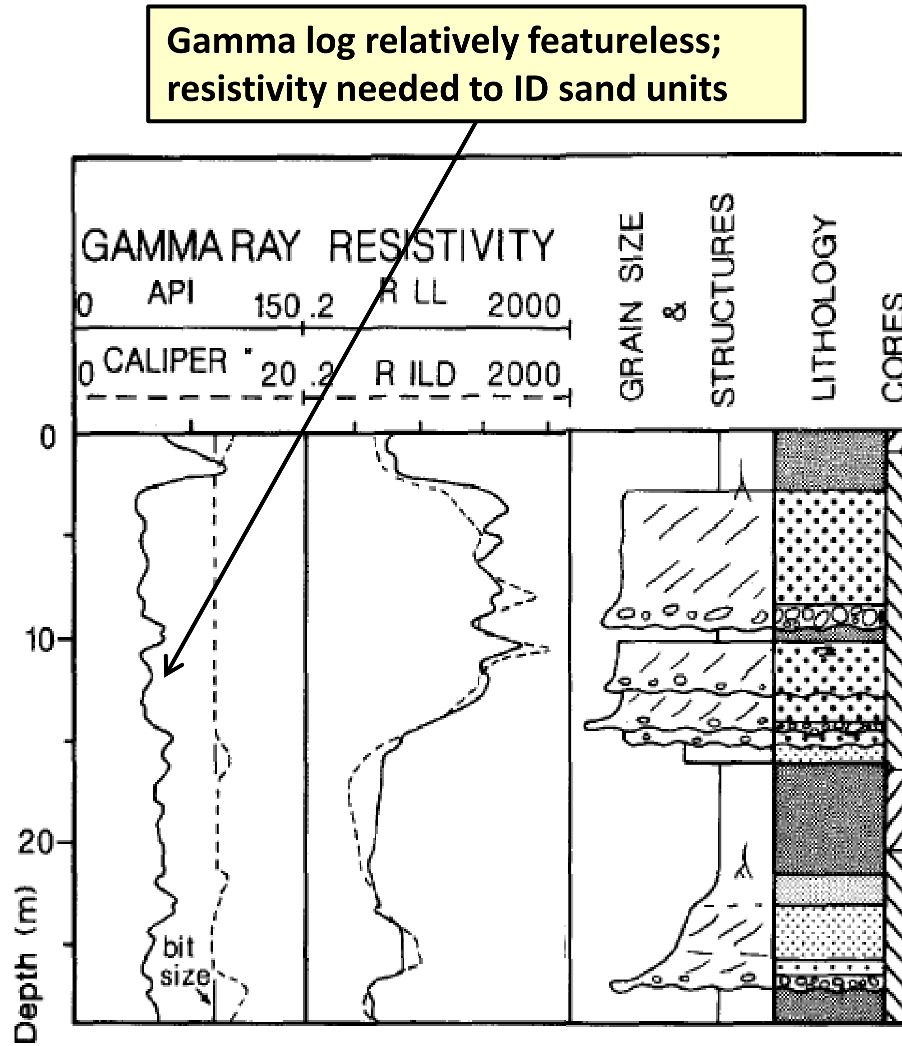


(Keys 1989)

Electrical Logs (cont'd)



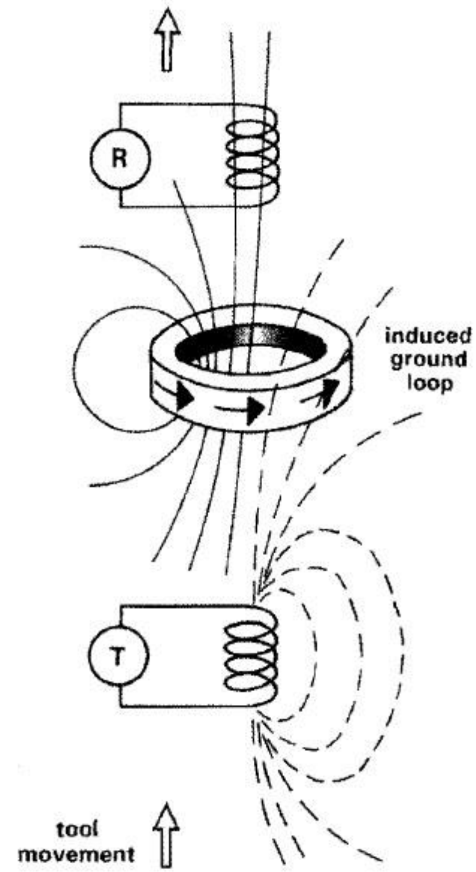
(Rider and Kennedy 2011)



(Modified from Rider 1990)

EM Induction

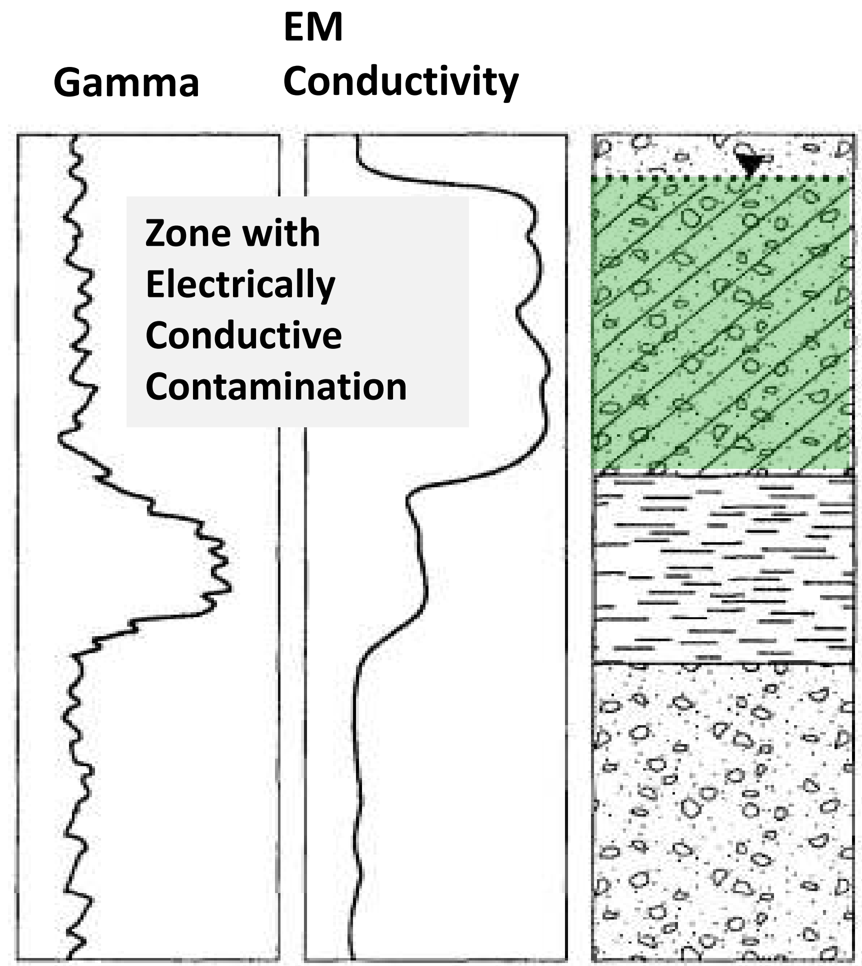
- Current from transmitter induces magnetic field in formation
- Eddy currents create secondary electrical field proportional to conductivity of formation, measured at receiver coil
- Can derive
  - Resistivity (conductivity)
  - Magnetic susceptibility
- Open-hole or PVC
- Water- or air-filled



(Rider and Kennedy, 2011)

EM Induction (cont'd)

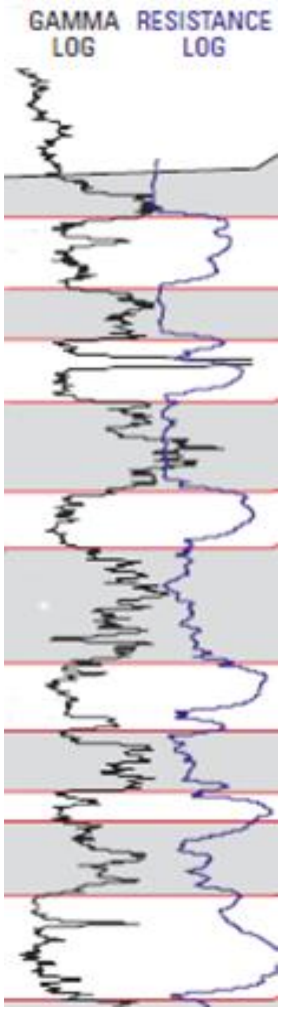
- Applications
  - Supplement to natural gamma, when NR or SPR not available (esp. to measure through PVC)
  - Saltwater intrusion
  - Other conductive GW contaminants (leachate, metals)



(Williams et al., 1993)

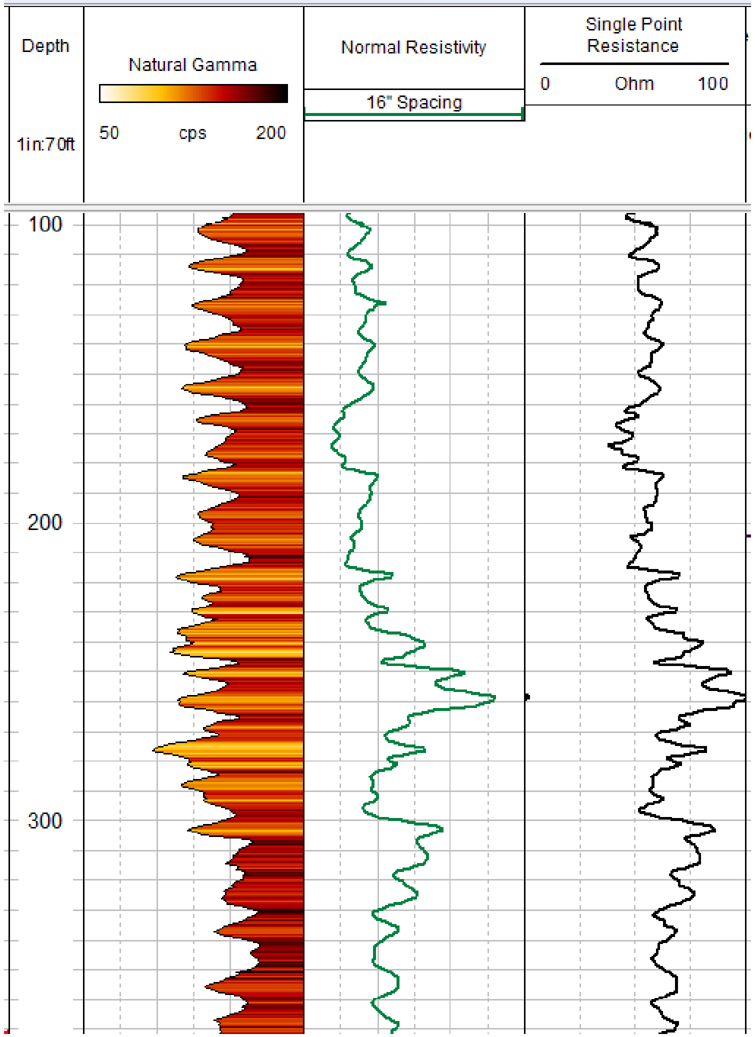
Logs Reveal Lithologic Changes, Identify Confining Units

Middle Stockton Formation



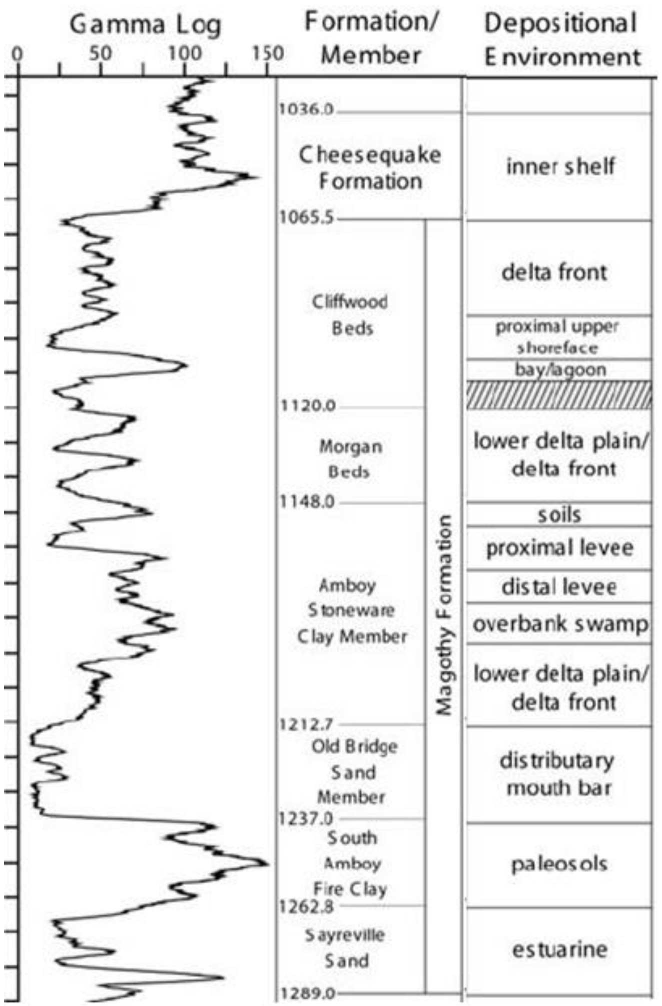
(Sloto 2007)

Passaic Fm. – Cyclic mudstone/siltstone; varying clay, organic carbon content



New Jersey Coastal Plain –

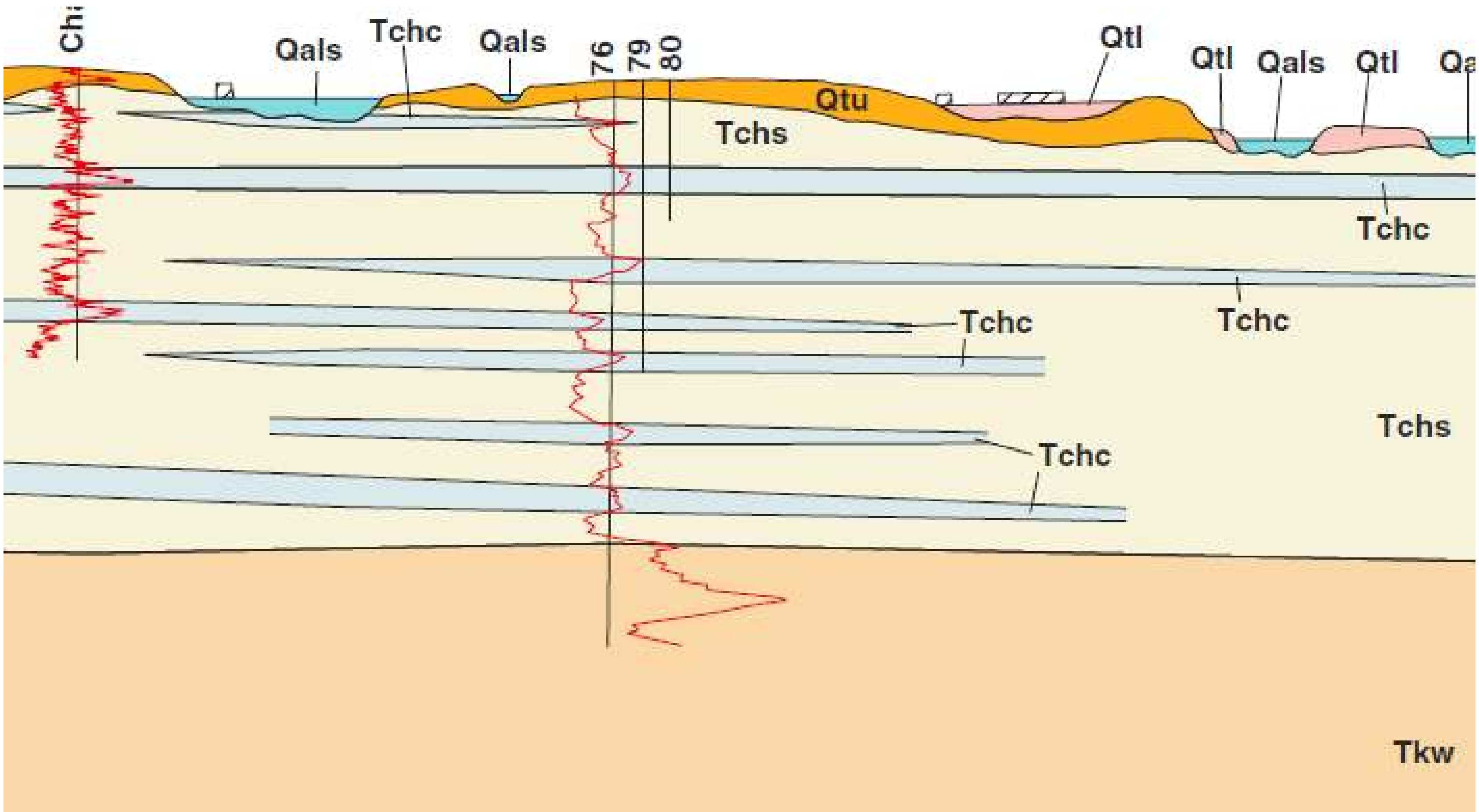
Units of the Magothy Formation



(Sugarman, Miller et al. 2005)

Used Extensively for Coastal Plain Units

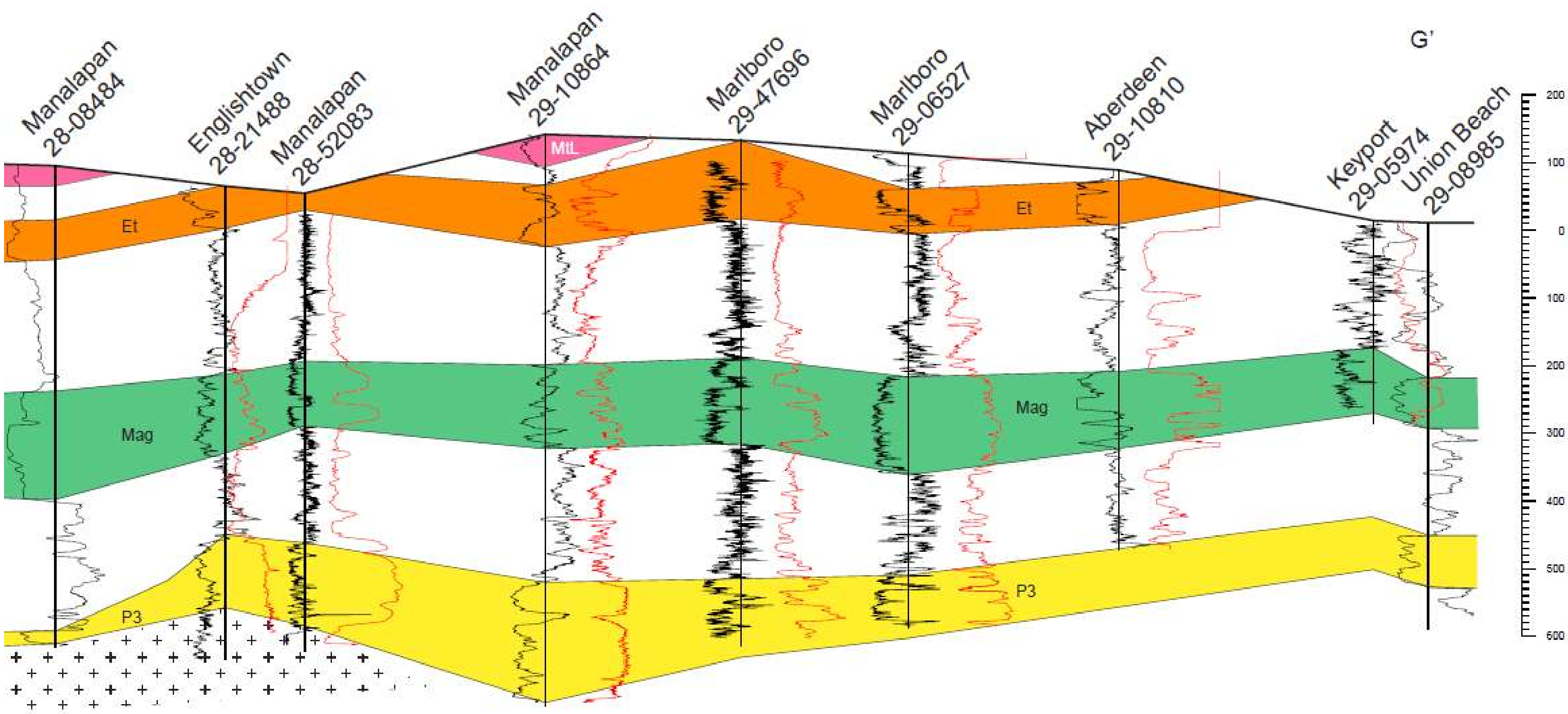
New Jersey Coastal Plain – Delineation of clay/sand facies within the Cohansey Formation; Identification of the top of the Kirkwood Formation confining unit



(Stanford, 2012)

Coastal Plain Framework based on Logs

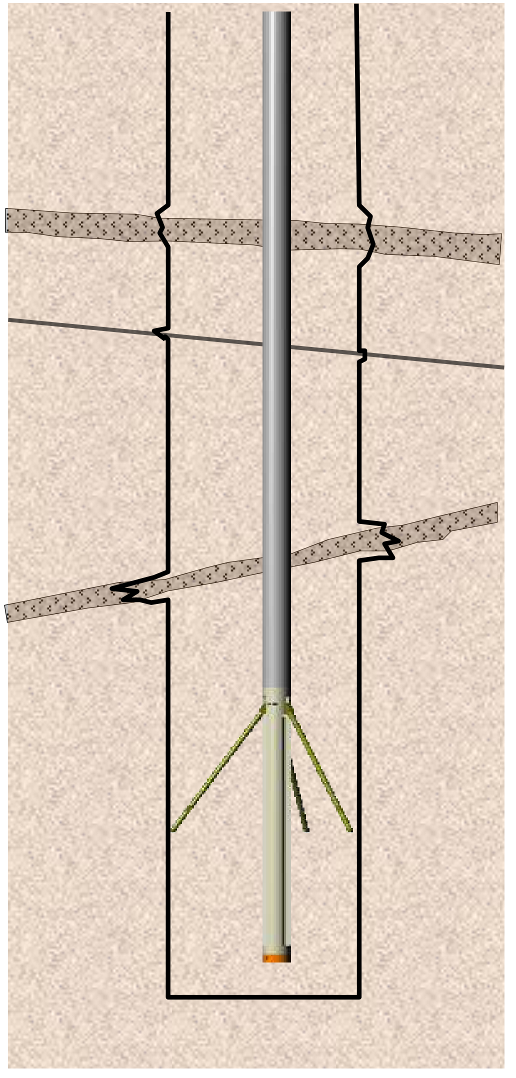
New Jersey Coastal Plain – Delineation of Aquifer Units



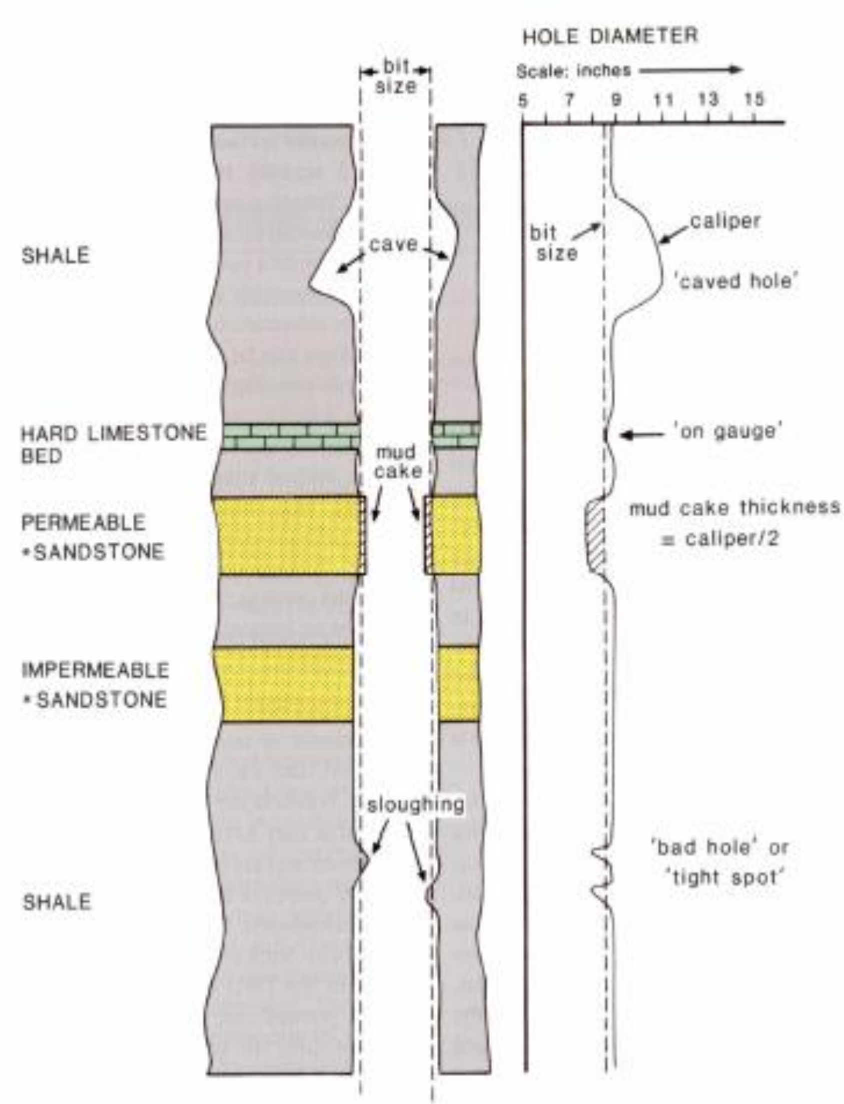
(Sugarman et al., 2013)

Caliper Logs

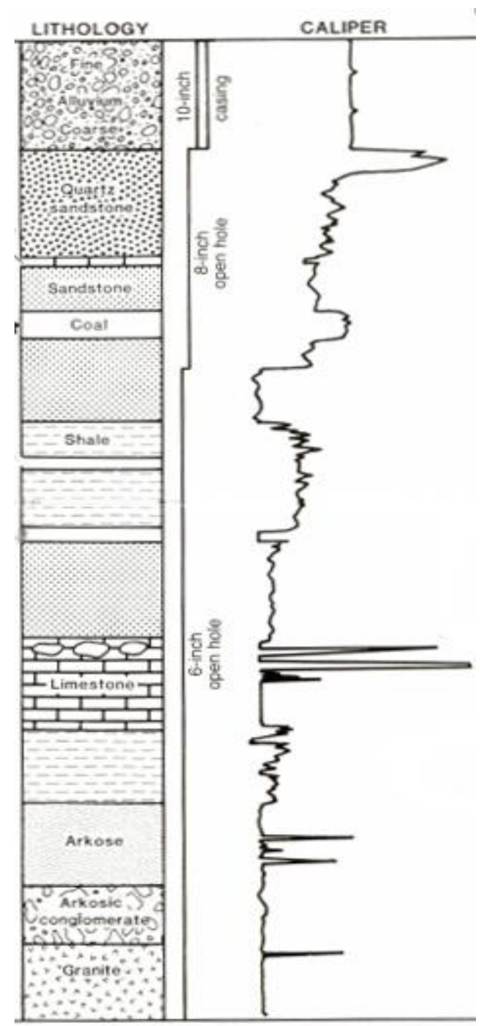
- Mechanical Three-Arm Tool
- Records Hole Diameter
- Used to Interpret
  - Depth of Casing
  - Fractures
  - Washout zones
  - Lithology Changes
- Used in Open Holes



Caliper Logs (cont'd)



(Rider and Kennedy 2011)



(Keys 1989)

Fluid Logs

- Temperature and Resistivity of fluid column in the well or borehole
- Main use is for initial location of hydraulically active fractures or zones
  - Inflections indicate inflow or outflow
  - Constant values over an interval may indicate cross-flow between hydraulically active fractures
- Can be used quantitatively e.g., via brine tracing (Michalski and Klepp 1990)

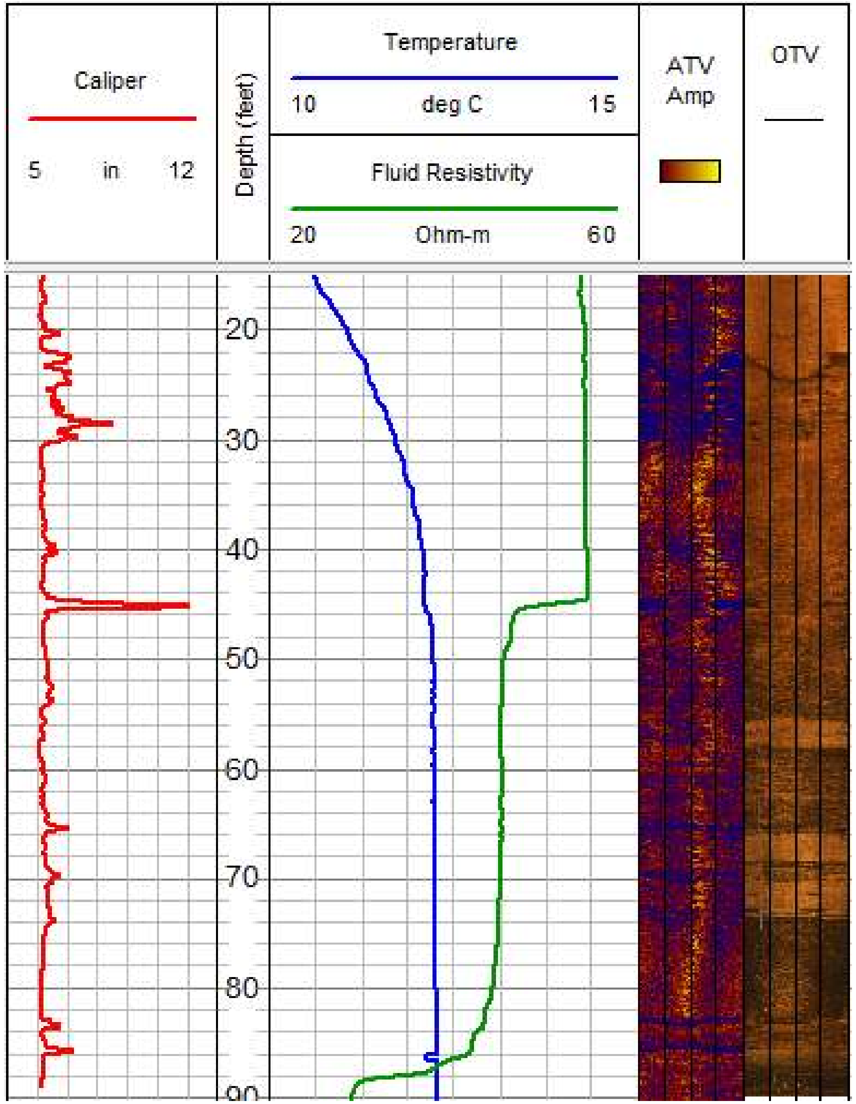
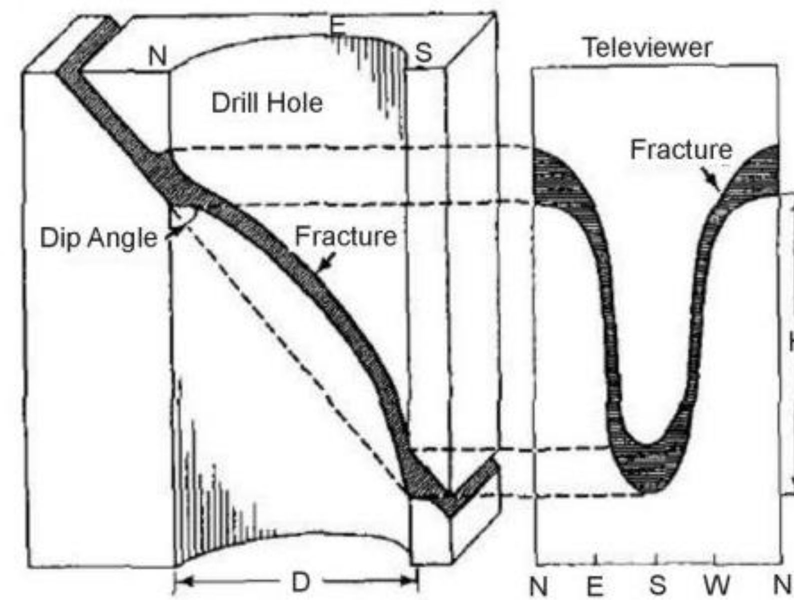


Image Logs

- Centralized ATV and OTV
- Circular traces vertically combined
- Cylindrical record “cut” at North, laid flat
- Log analyst selects and classifies planar features, which plot as sinusoids
- 3D positioning sensors and software allow reporting of structural measurements to North



(Wightman et al., 2003)

Image Logs (cont’d)

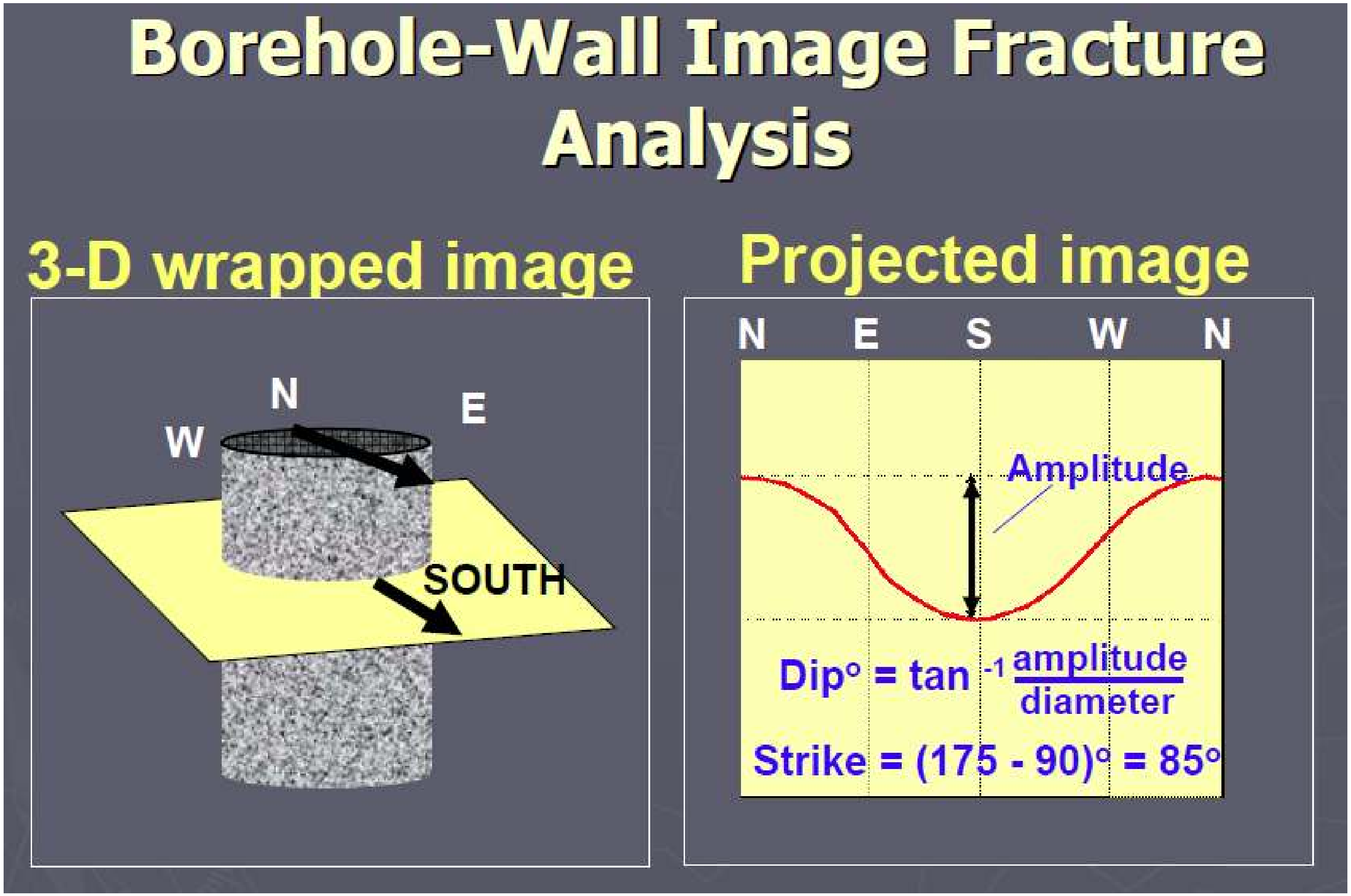
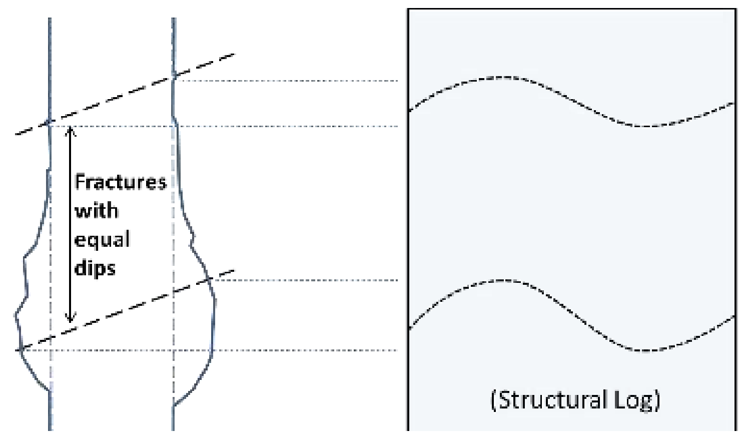


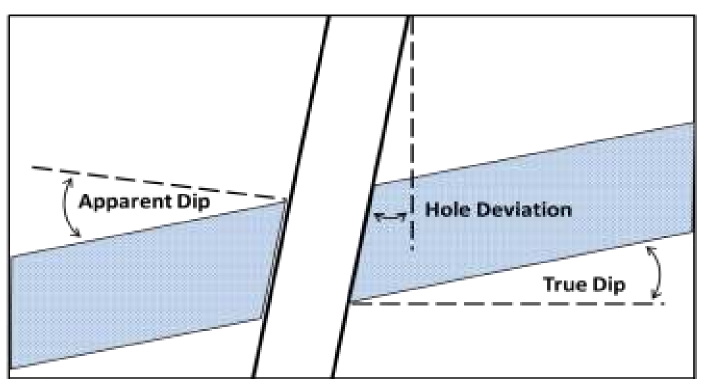
Image Logs (cont'd)

- Image Log Analysis Workflow
  - Normalize image for centralization, colors
  - Correct for magnetic interference just below steel casing
  - Evaluate and correct for borehole diameter effects
  - Select and classify planar features
  - Correct for borehole deviation
  - Adjust for magnetic declination (to True N)

Greater amplitude in washout interval overestimates dip; correction for increased borehole diameter required



Apparent vs. True Dip; Need to correct for deviated borehole



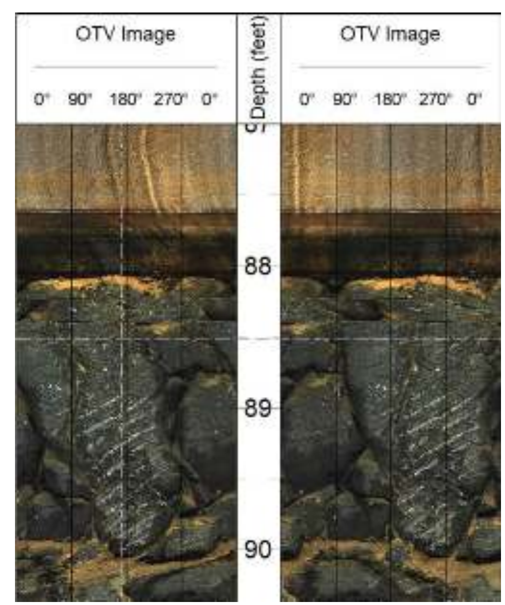
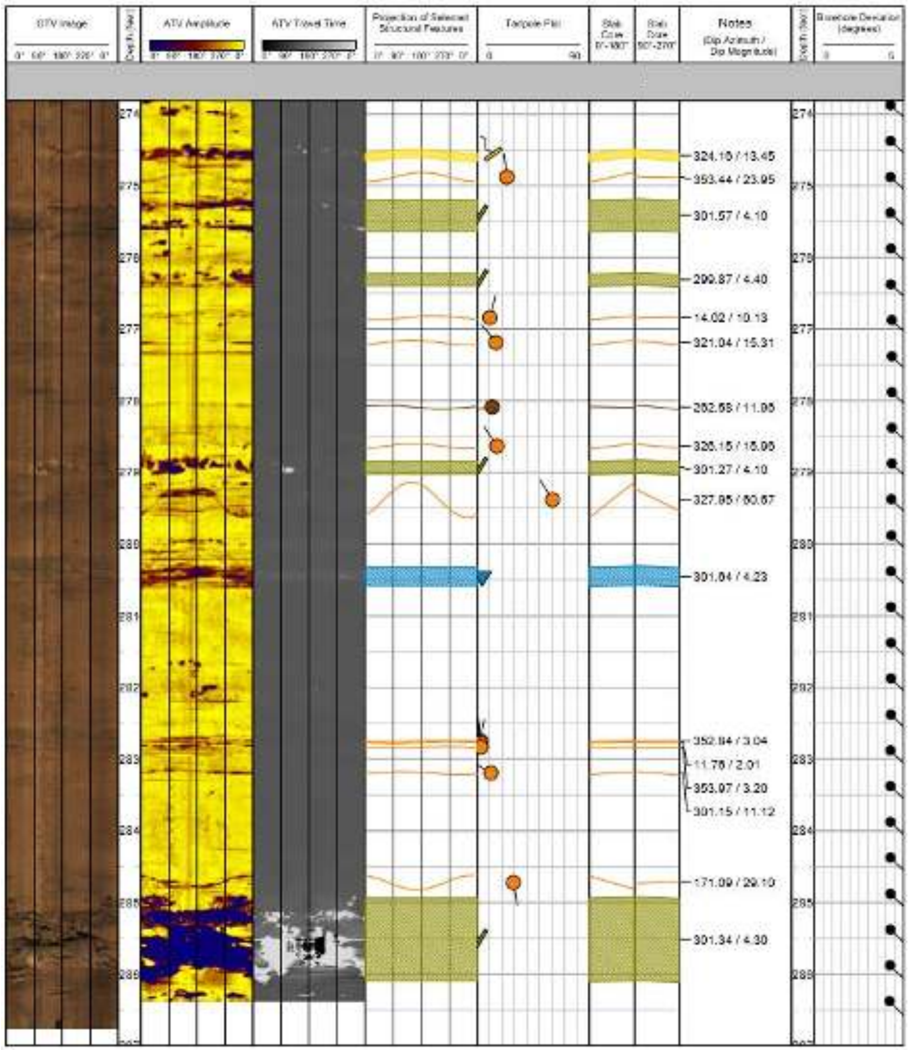
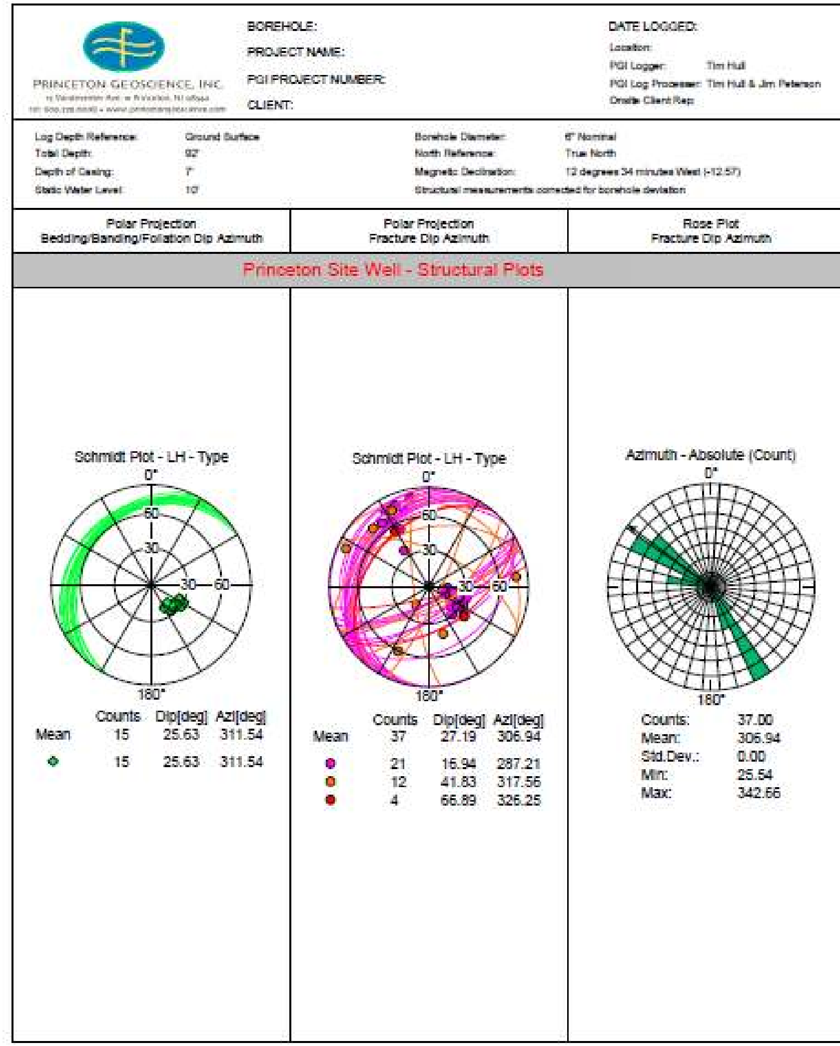
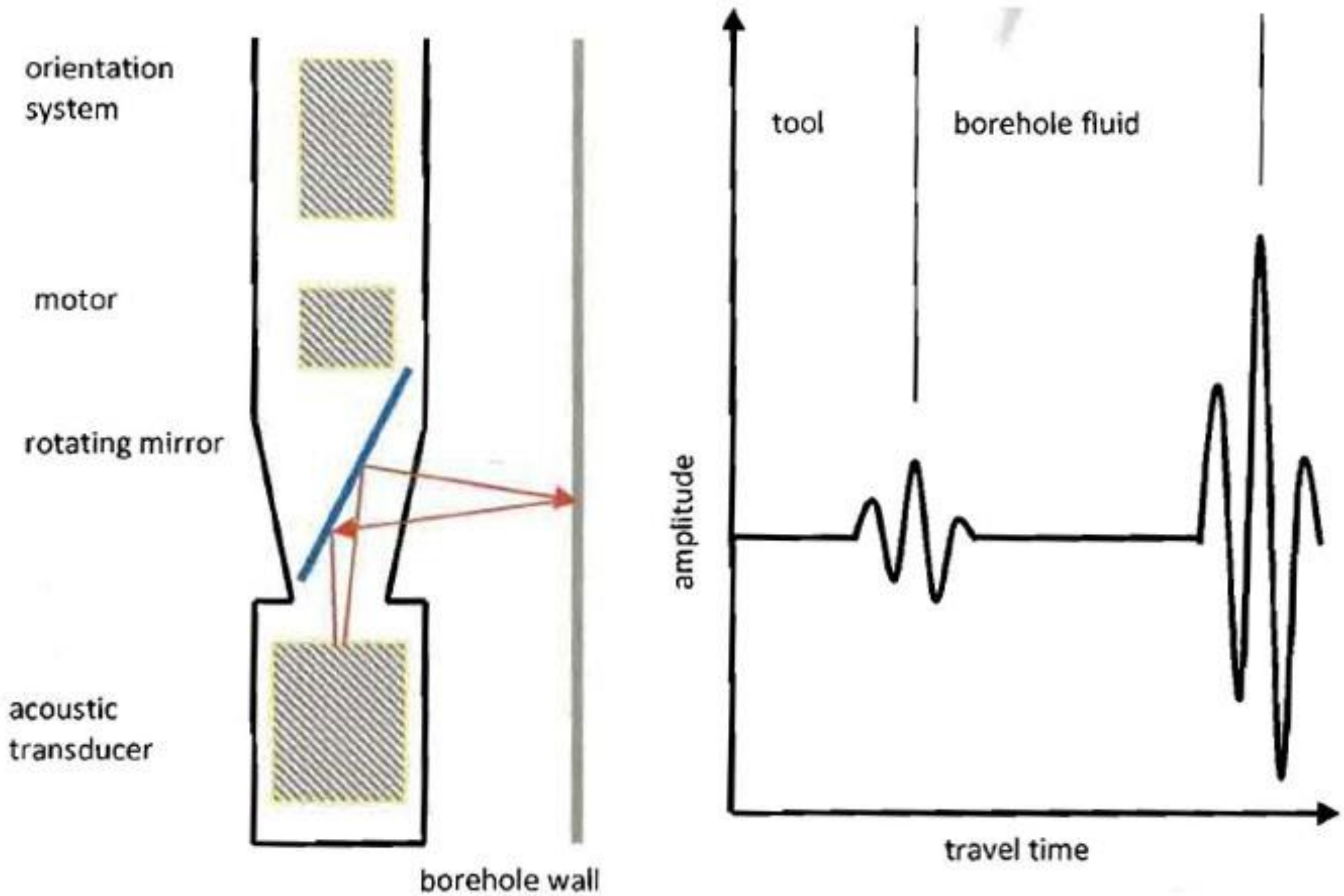


Image Logs (cont'd)





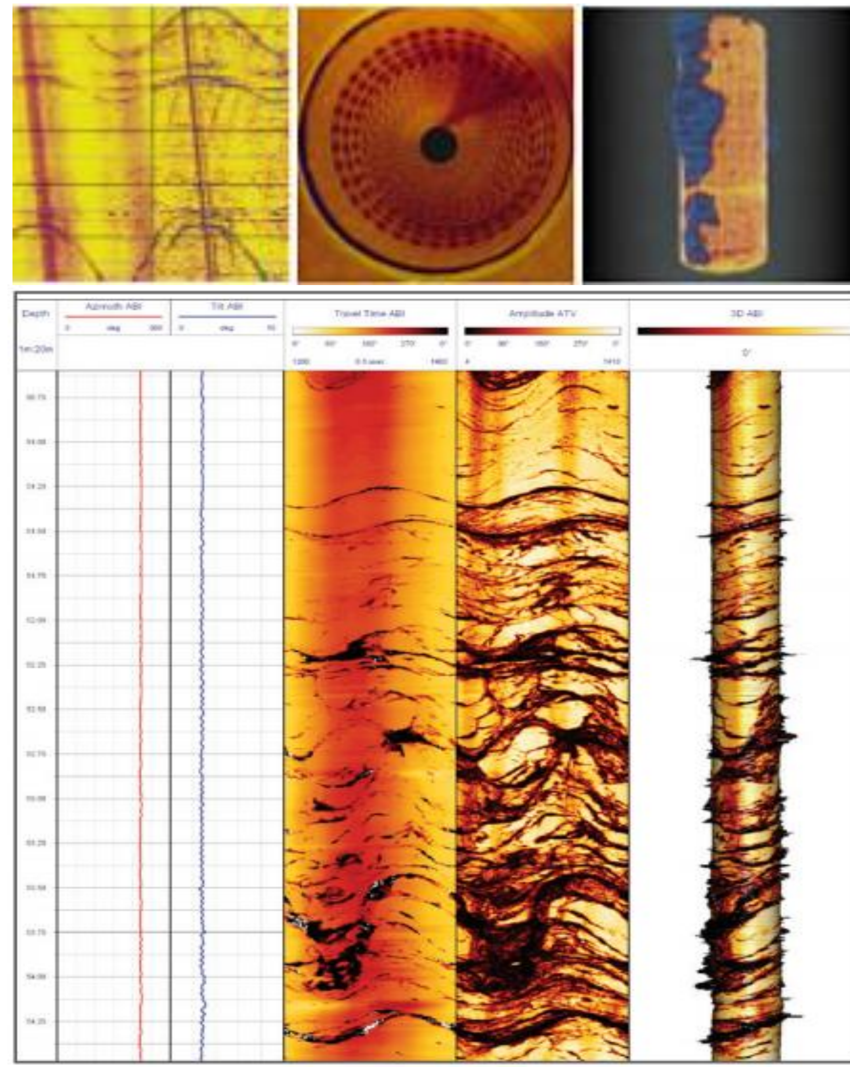
Acoustic Televiewer



(ALT, 2014)

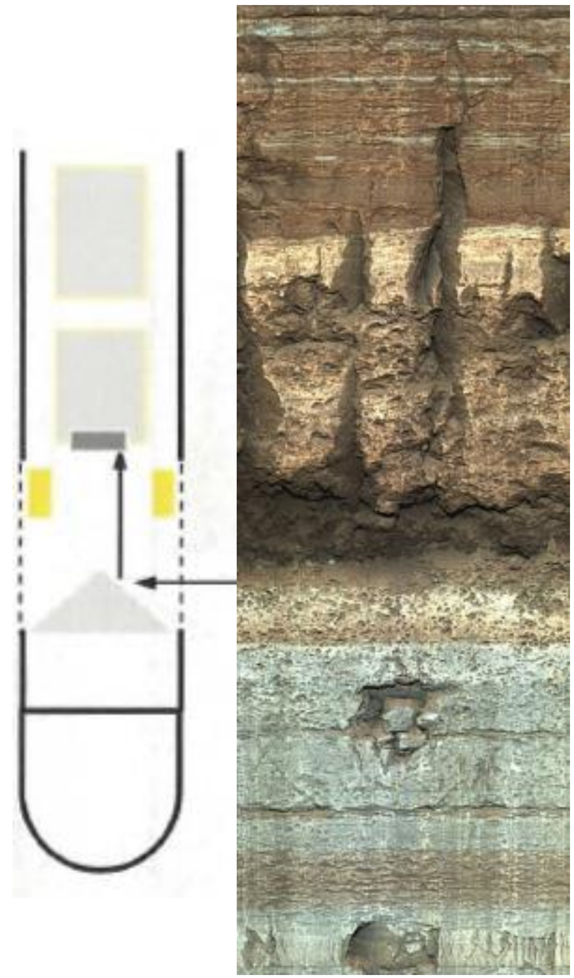
Acoustic Televiewer

- Imaging in mud- or water-filled holes
- Structural evaluation
- Acoustic caliper
- Multi-echo mode for measurements through PVC pipe
- Pipe-inspection mode for inner and outer corrosion, wall thickness
- Can use quantitative data, including cross-plotting with other data (e.g. mean amplitude with gamma for lithology)



(ALT, 2015)

Optical Televiewer



(ALT, 2015)

Optical Televiewer

- Imaging in air- or clear water-filled holes
- Planar features
  - Bedding, foliation, layering
  - Fractures
    - Open or mineralized
    - Apparent aperture
- Visual inspection
  - Staining, NAPL
  - Flow indicators
  - Well condition

Compositional layering, fracture in basalt

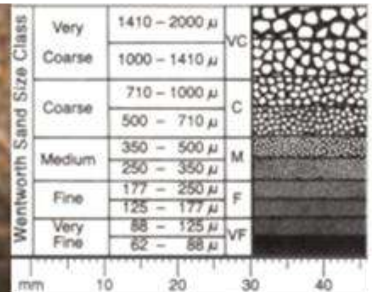
Optical Televiewer

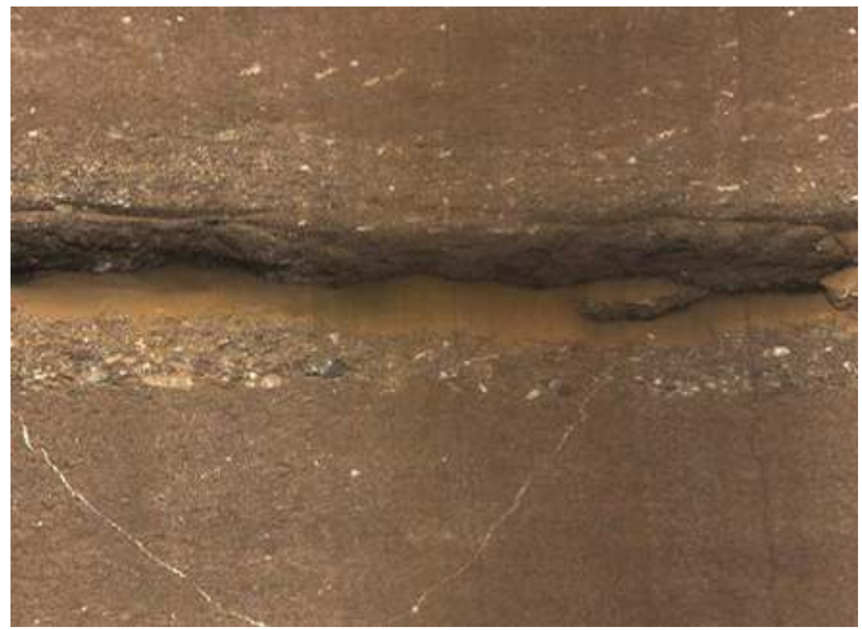
Large Bedding Plane Fracture at 270’

Bedding Plane Fracture @ 177.5’

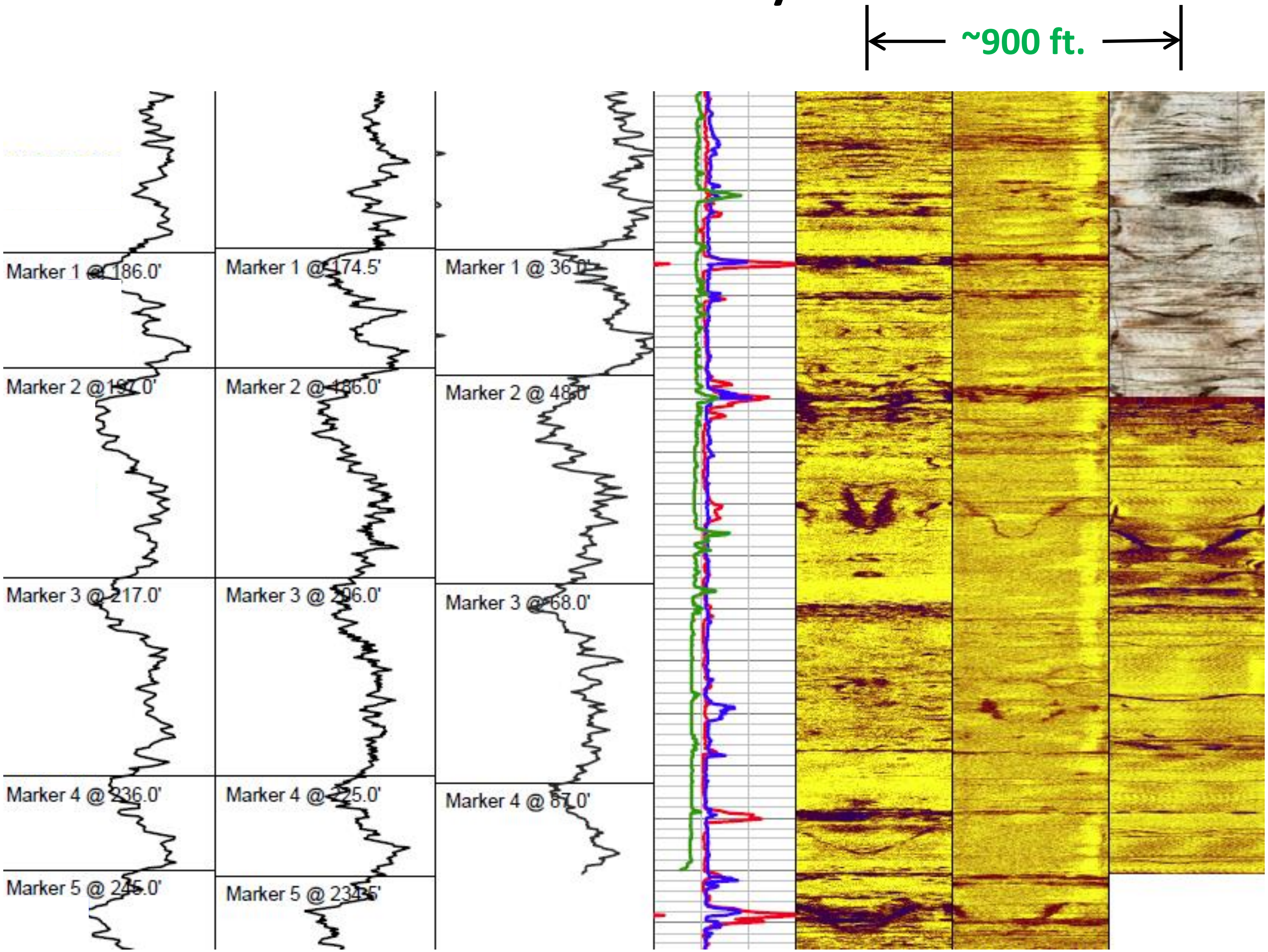
Steeply-Dipping Mineralized Fractures @ 65’ to 67’

Optical Televiewer



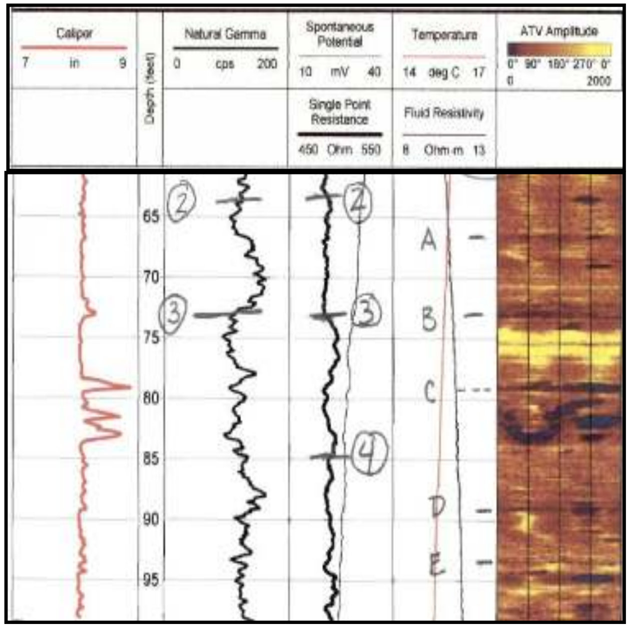


Correlated Logs Show that Bedding Fractures are Laterally Continuous

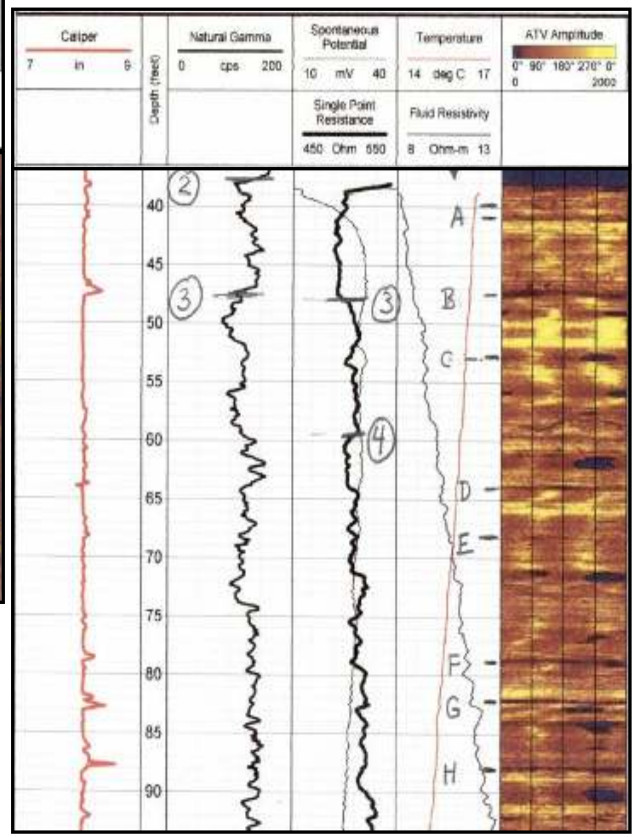


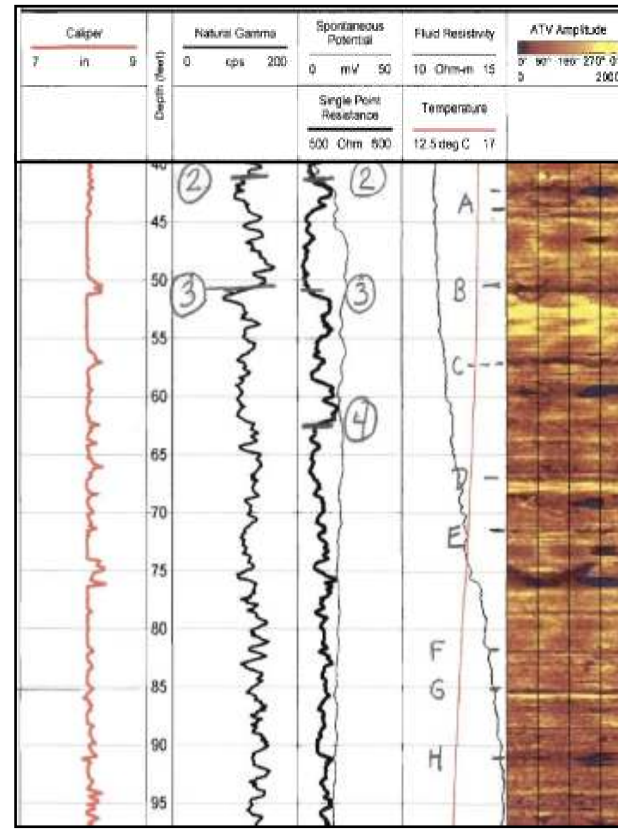
Logs Vertically Shifted to show Correlation; Individual Rock Units and Bedding Fractures can be Traced Hundreds of Feet across a Site in Mudstones

Boring Located Down-Dip



Borings Positioned Nearly Along Strike from One Another



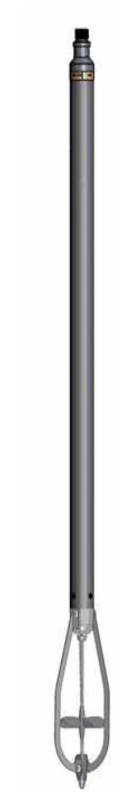


Ground surface elevations at borings are similar, so <u>depths of markers</u> shown on logs give a good general indication of bedrock structure

Flow Meters

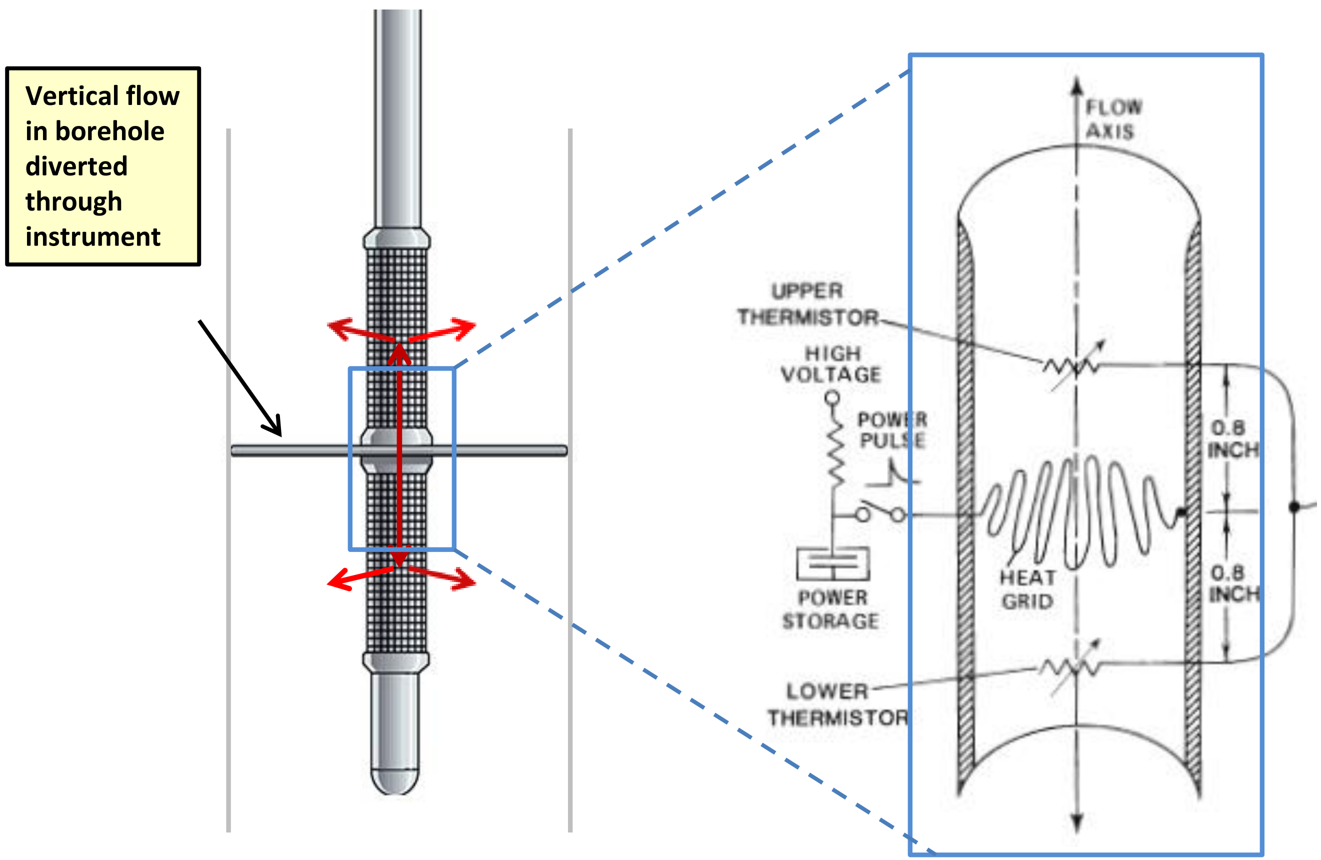
- Measure Vertical Flow in Well as Indicator of Conditions in Adjacent Aquifer
  - Standard HPFM range 0.03-1.0 GPM; NJGS modified unit up to 7 GPM in 6-inch holes
  - Spinner Flow Meter ~2-10+ GPM; lower rates require trolling
- Ambient or Pumping
- Multiple Wells

HPFM

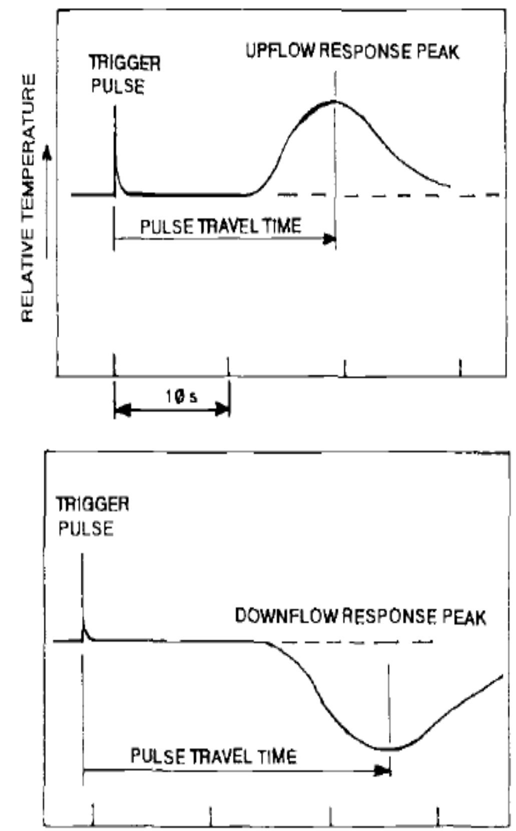


Spinner

HPFM Operation and Response

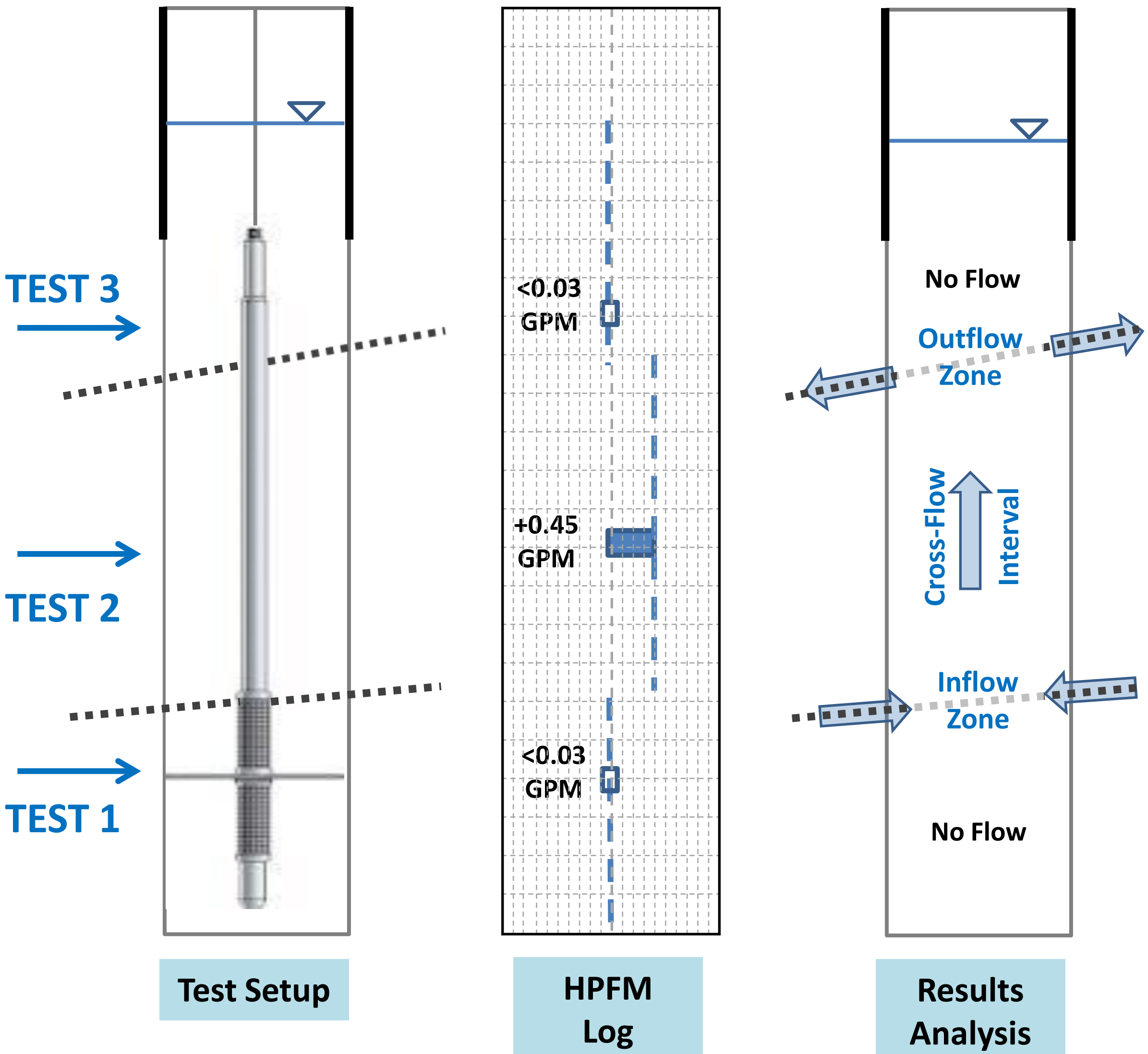


(Hess 1986)



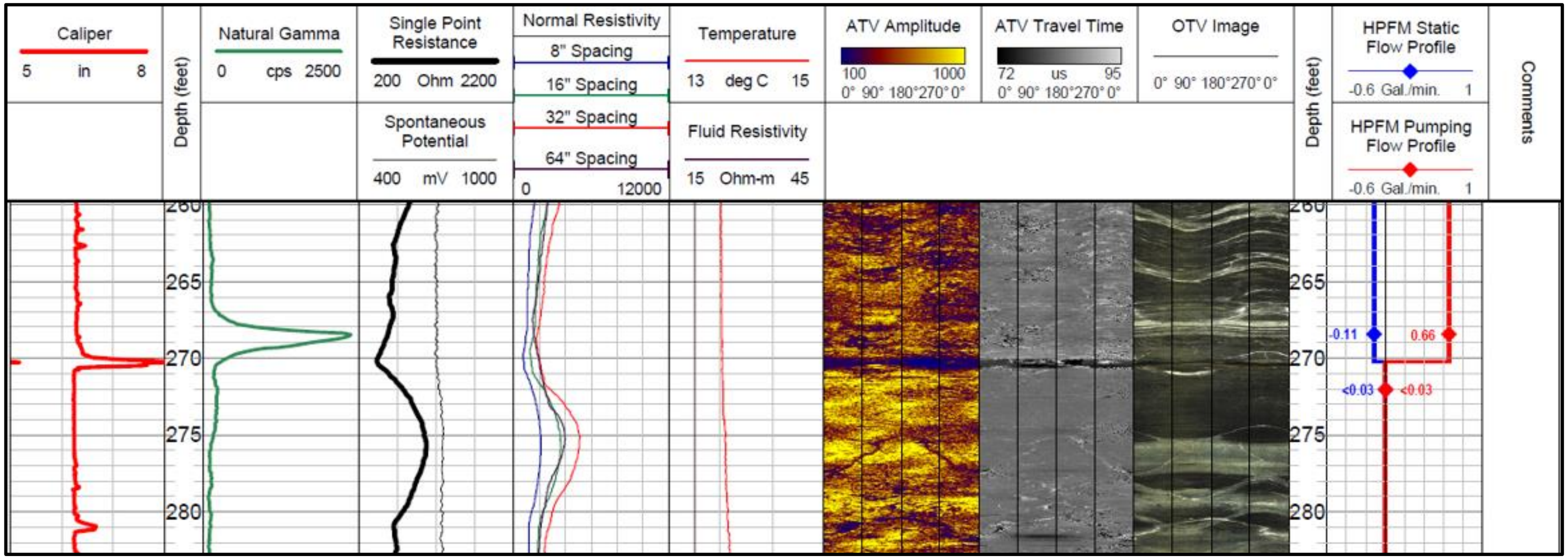
(Hess and Paillet 1990)

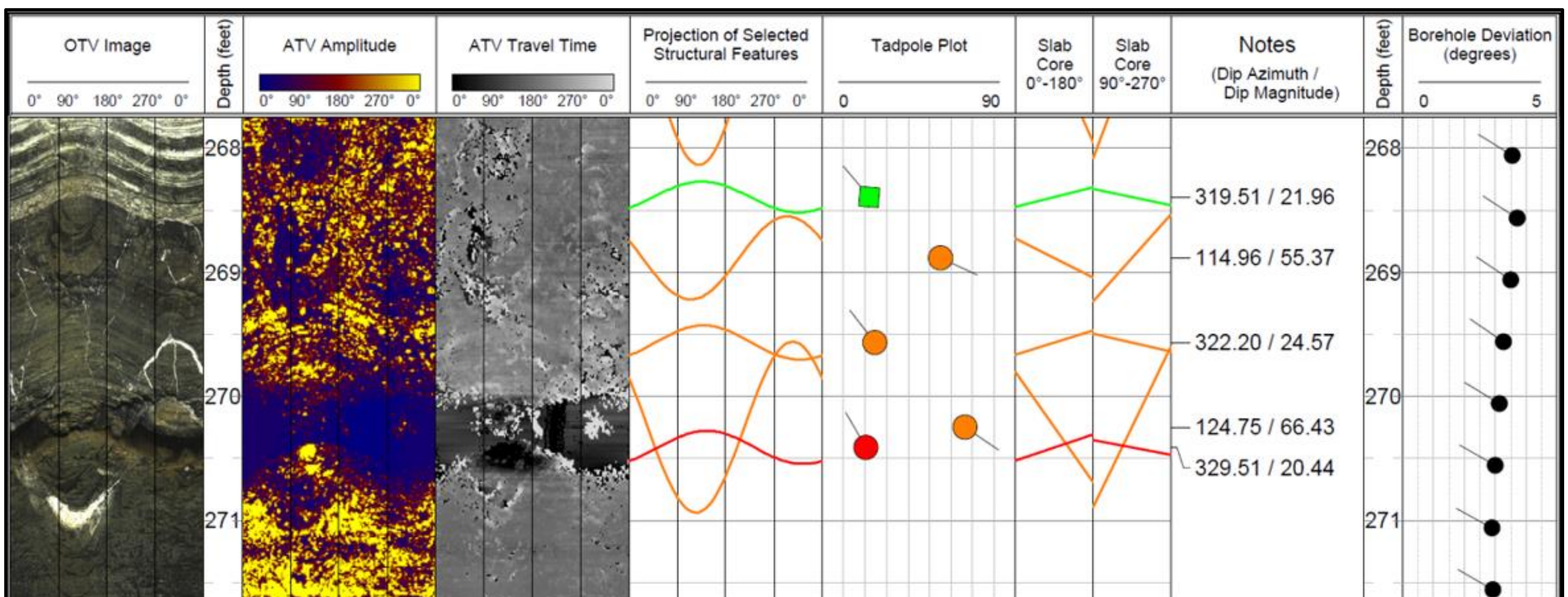
HPFM Quantifies Cross-Flows



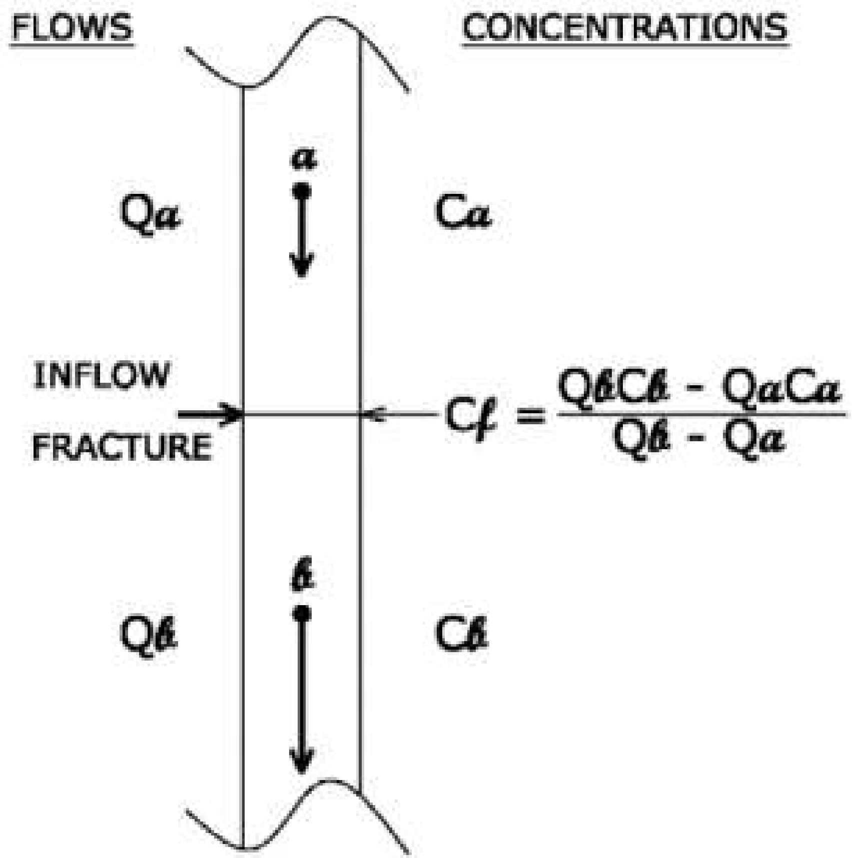
- Upward Flow implies Higher Head in Deep Zone
- Water Level in Well is Composite Head
- Vertical Cross-Flow Causes Mixing, Possible Spread of Contamination
- 0.45 GPM ~ 650 GPD – Could be Significant Issue
- Easily Remedied (Install Screen and Gravel Pack Well)

HPFM – Transmissive Bedding Fracture





Assessing Inflow Zone Water Quality from Grab Sampling Results

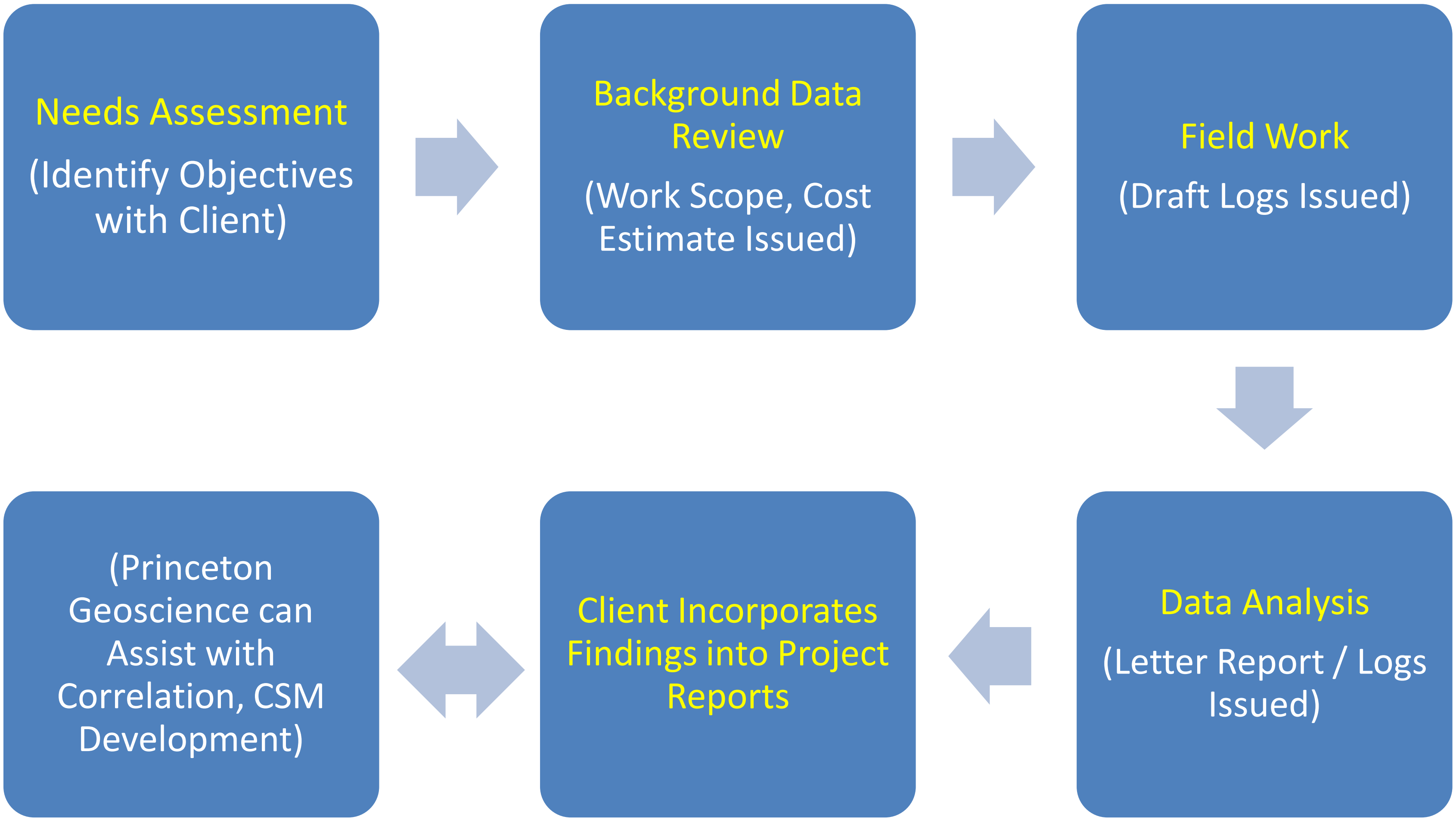


Groundwater chemistry of water entering at inflow zone (Cf) can be estimated based on:

- Vertical flow rates in well upstream (Qa) and downstream (Qb) of inflow zone (e.g., by HPFM), and
- Water quality in well upstream (Ca) and downstream (Cb) of inflow zone inflow zone (e.g., depth-discrete grab sampling)

(Michalski 2010; NJDEP-SRP 2012)

Logging Project Workflow



Additional Key Resources

- ITRC Guidance on Implementing Advanced Site Characterization Tools
  - Section 4: https://asct-1.itrcweb.org/4-borehole-geophysics/
- NJGWS Bulletin 77
  - Herman, G. (2010). Hydrogeology and Borehole Geophysics of Fractured-Bedrock Aquifers, Newark Basin, New Jersey. Contributions to the geology and hydrogeology of the Newark basin. G. C. H. a. M. E. Serfes, NJ Geological Survey. **Bulletin 77:** F1-F45.
- USGS Hydrogeophysics Branch
  - https://water.usgs.gov/ogw/bgas/

END

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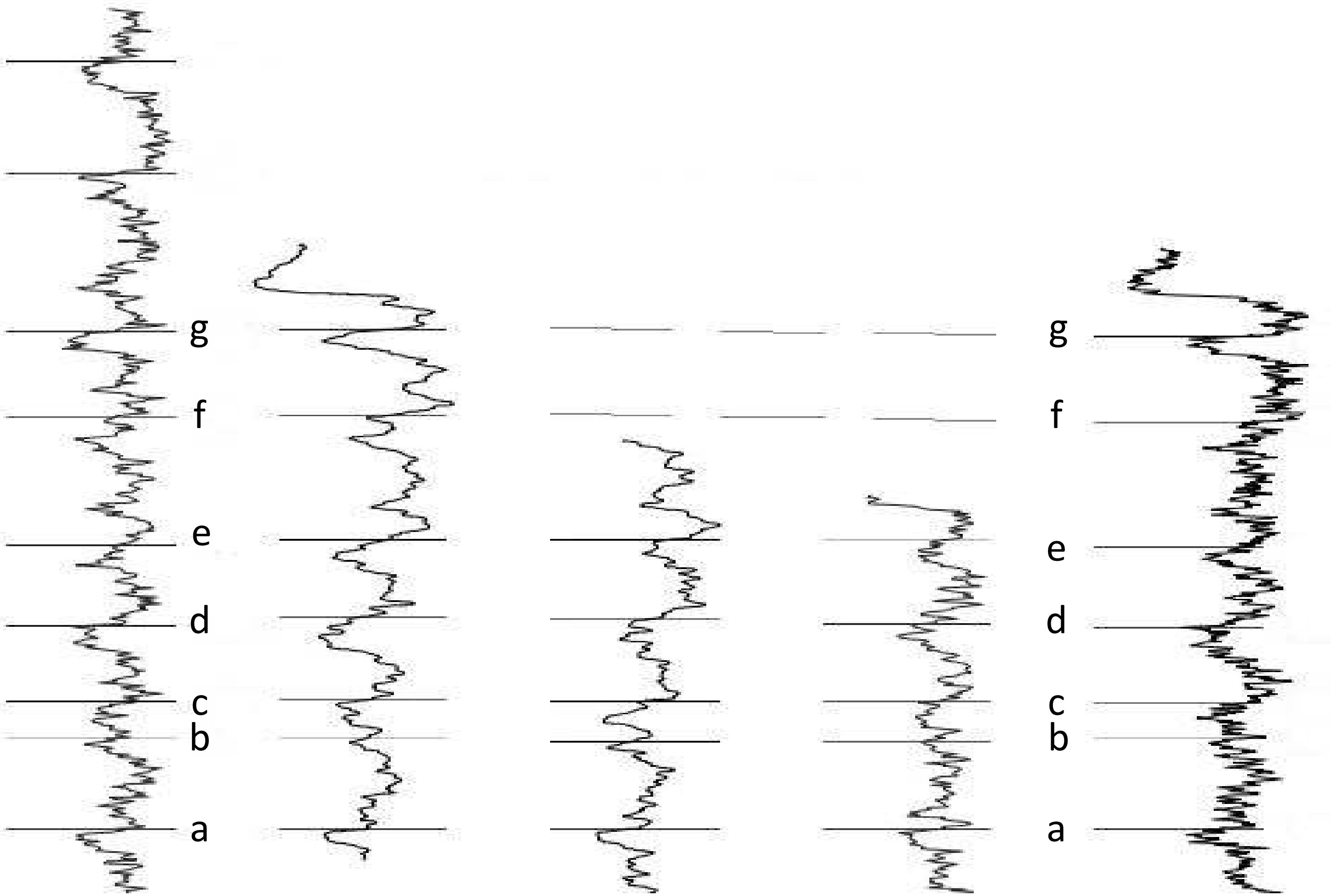
SUPPLEMENTAL INFO

Case #3: Central NJ Newark Basin

- Mudstone bedrock (Passaic Formation)
- Extensive prior investigations, including some geophysical logging, packer testing
- Conflicting views regarding structure, applicability of LMAS concepts at the site
- Geophysical logging scope:
  - Extensive gamma logging, outcrop mapping to clarify structure
  - OTV, ATV and HPFM to better understand pathways, flow
  - Integration of GP logging and packer results
- Confirmed "textbook" LMAS conditions – systematic nature of flow system allows LSRP to be confident of RI completion and planned monitoring

Markers Identified on Gamma Logs and Correlated from Well to Well

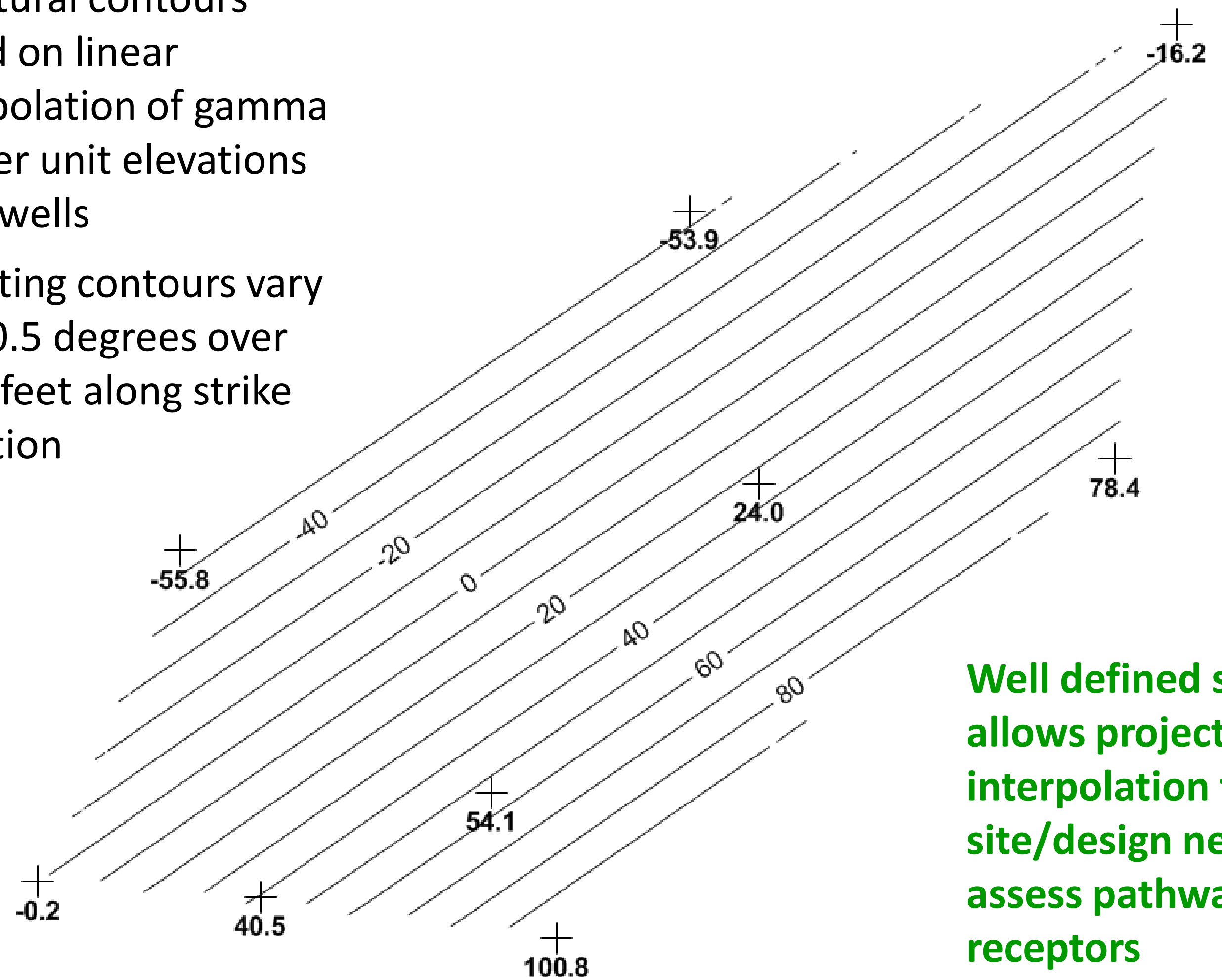


>20 Laterally Continuous, Parallel Gamma Markers Identified

WELL ID		Well 1	Well 2	Well 3	Well 4	Well 5	House 1	House 2	Site-Wide Separation of Stratigraphic Markers	
WELL LOGGED BY		Princeton Geoscience	Princeton Geoscience	Princeton Geoscience	Princeton Geoscience	Princeton Geoscience	Company #2	Company #3		
DATE OF LOGGING		06/23/13	06/23/13	06/23/13	06/24/13	06/24/13	03/25/97	12/10/05	Mean Value	Standard Deviation
REFERENCE ELEVATIONS	PVC	304.47	299.55	265.72	287.34	264.47	*	*		
	RISER	304.79	299.73	265.89	287.58	264.66	270.64	293.66		
	GROUND	302.4	295.6	263.2	284.7	261.7	267.0	*292.6*		
LOGGING REFERENCE		PVC	PVC	PVC	PVC	PVC	RISER	RISER		
MARKERS INTERSECTED		a - f	c - f	a - f	d - f	c - e	b - f	a - f		
f	Depth	181.0	190.0	23.0	89.0		112.5	192.5		
	Elevation	123.5	109.6	242.7	198.3		158.1	101.2		
Separation		22.5	23.5	23.0	24.0		22.5	22.0	22.9	0.7
e	Depth	203.5	213.5	46.0	113.0	35.0	135.0	214.5		
	Elevation	101.0	86.1	219.7	174.3	229.5	135.6	79.2		
Separation		11.5	12.0	13.0	12.5	13.0	13.0	11.5	12.4	0.7
d	Depth	215.0	225.5	59.0	125.5	48.0	148.0	226.0		
	Elevation	89.5	74.1	206.7	161.8	216.5	122.6	67.7		
Separation		20.0	19.5	21.0		20.0	20.0	20.0	20.1	0.5
c	Depth	235.0	245.0	80.0		68.0	168.0	246.0		
	Elevation	69.5	54.6	185.7		196.5	102.6	47.7		
Separation		18.0		17.5			19.0	19.0	18.4	0.8
b	Depth	253.0		97.5			187.0	265.0		
	Elevation	51.5		168.2			83.6	28.7		
Separation		11.0		11.5				9.5	10.7	1.0
a	Depth	264.0		109.0				274.5		
	Elevation	40.5		156.7				19.2		

Gamma Correlations Imply Laterally Continuous, Planar Bedding Units

- Structural contours based on linear interpolation of gamma marker unit elevations at all wells
- Resulting contours vary by < 0.5 degrees over ~600 feet along strike direction

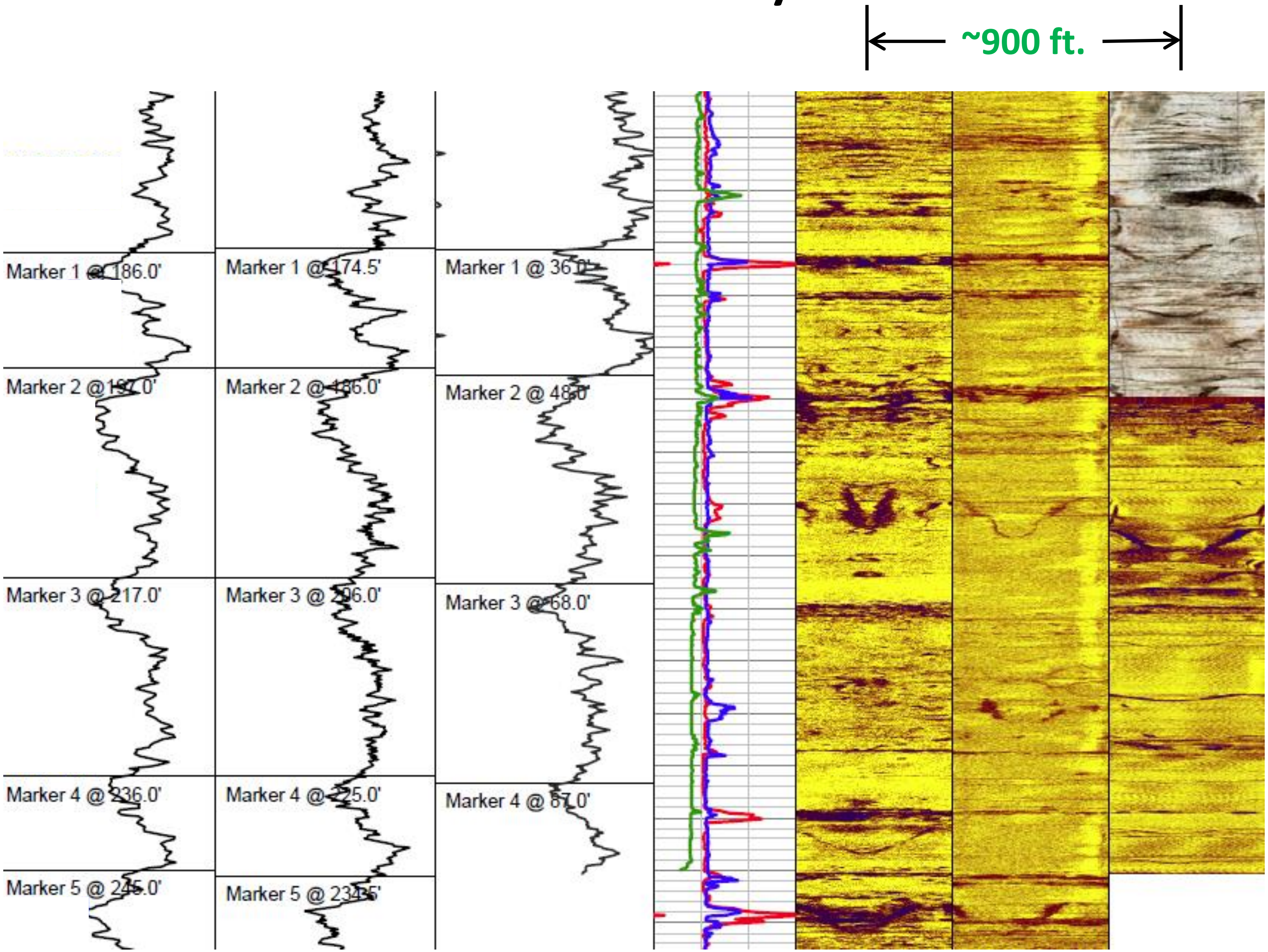


Well defined structure allows projection or interpolation to site/design new wells, assess pathways to receptors

But…What about the Fractures?

- Bedding orientation only useful for understanding flow pathways to the extent bedding fractures are also present and continuous
- ATV, OTV and Caliper logs, when vertically aligned based on previously identified Gamma markers, reveal:
  - Numerous bedding fractures that are laterally continuous across the site – ATV/OTV very similar from well to well
  - Some fractures at interface between hard and soft rocks
- Lateral extensiveness of bedding fractures should not be surprising at this site, because
  - Gamma shows the rock units themselves are continuous, and
  - Bedding fractures reflect mechanical properties of the of the rocks

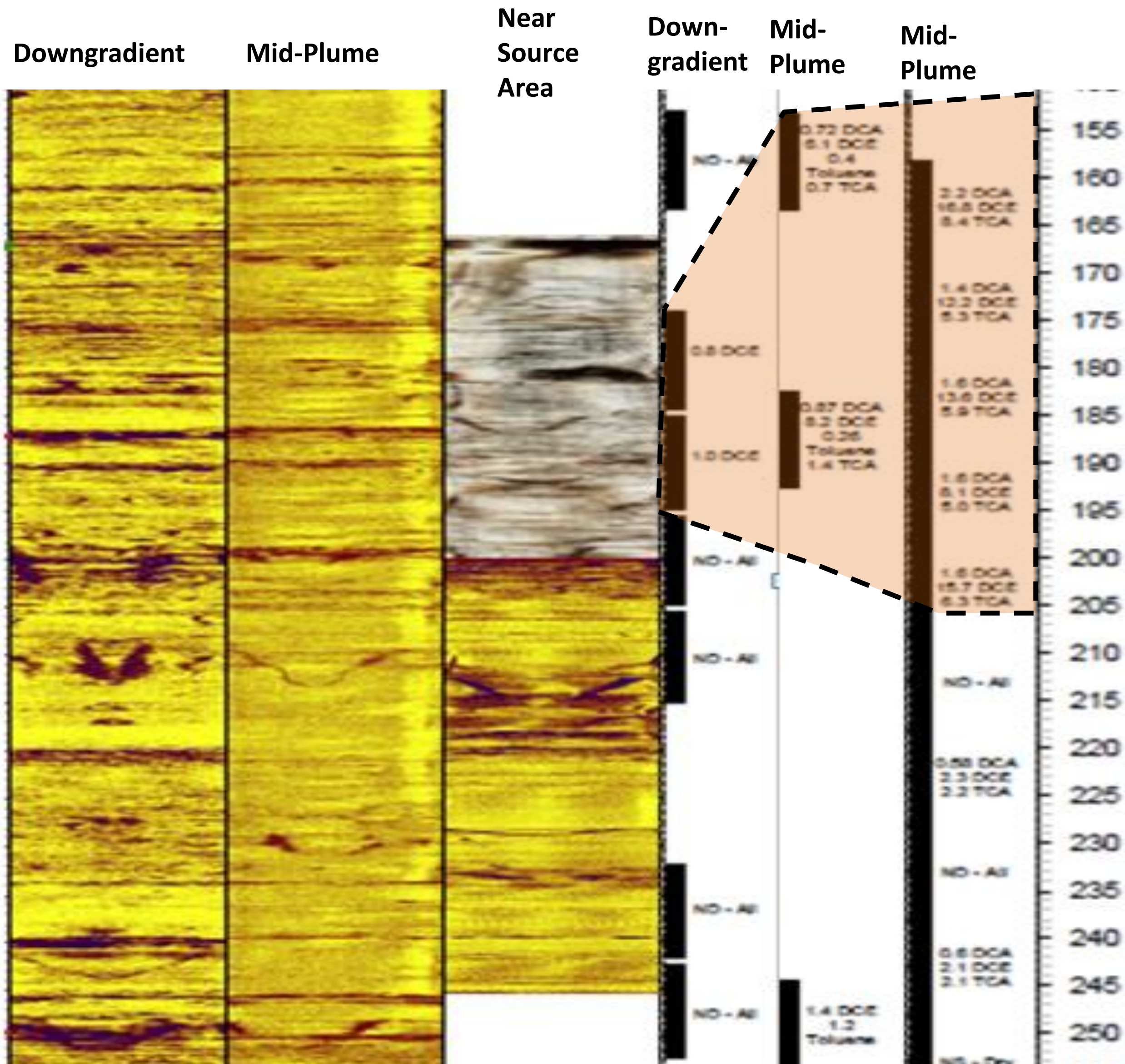
Correlated Logs Show that Bedding Fractures are Laterally Continuous



OK, but What's the Effect on Plume Geometry? How about the High Angle Fractures?

- The plume appears to inhabit the same fractures into which source area recharge occurs
- Older packer testing data shows some vertical spreading, but those data may reflect leakage (packers set without use of a caliper log to ID a smooth seating zone)
- Latest, most distal packer testing shows VOC impact only in bedding unit fractures that sub-crop below the former source area
- Limited vertical spreading of plume, despite very strong vertical gradients between individual bedding-parallel flow zones and the presence of some high-angle fractures connecting zones
- Conditions consistent with LMAS concepts of Michalski and Britton.

ATV, OTV, Caliper and Packer Test Comparison

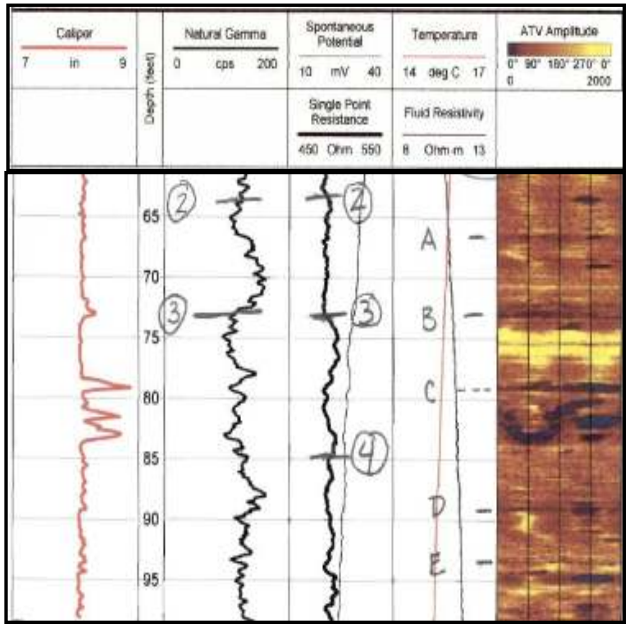


Case #4: Central NJ Newark Basin

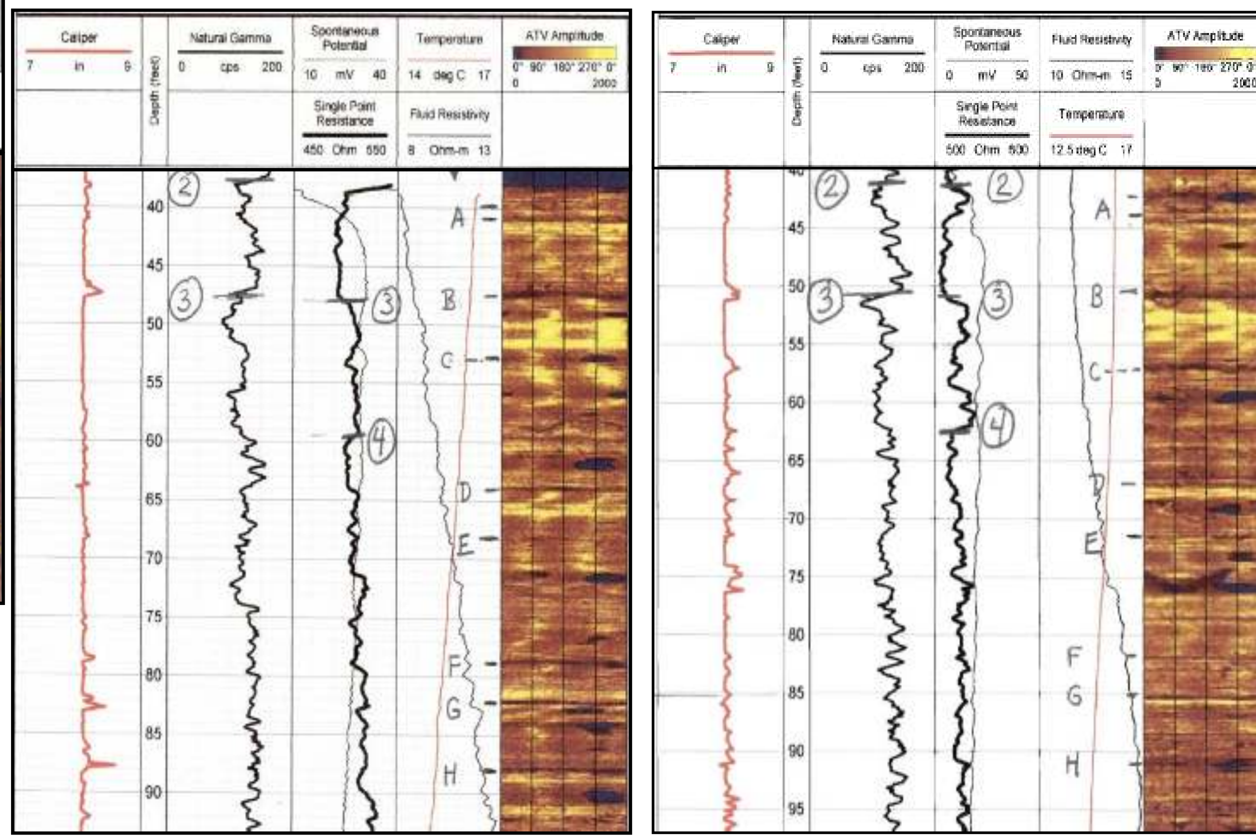
- Mudstone bedrock (Passaic Formation)
- NJGS mapping suggested potentially complex structure (faults and folds)
- Former drycleaner site with several existing bedrock wells; LSRP updating CSM, completing RI
- Geophysical logging scope:
  - Gamma, electrical, OTV, ATV and HPFM of three 100-foot test holes, which will later be converted to monitoring wells
  - Assess structure, presence and lateral continuity of fractured flow zones
- Results indicate another site where LMAS principles apply well
  - Gamma and SPR markers subtle, but correlated site-wide
  - Individual bedding plane fractures traceable across site
  - Planar structure, no disturbance by folding or faulting at scale of concern for site groundwater investigation
  - Open interval of existing, VOC-impacted down-dip well shown to be intersected by the same fractures that occur near ground surface in source area boring – plume appears to move along bedding plane fractures from point of intersection at source
- Assisted LSRP in selection of well completion depths – drilling now in progress

Logs Vertically Shifted to show Correlation

Boring Located Down-Dip



Borings Positioned Nearly Along Strike from One Another



Ground surface elevations at borings are similar, so <u>depths of markers</u> shown on logs give a good general indication of bedrock structure

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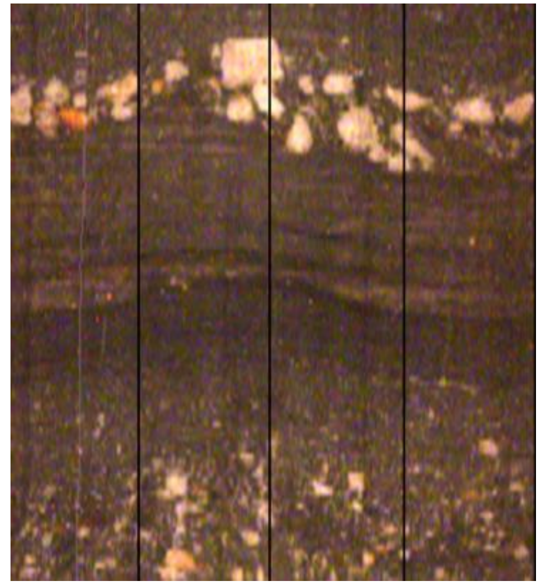
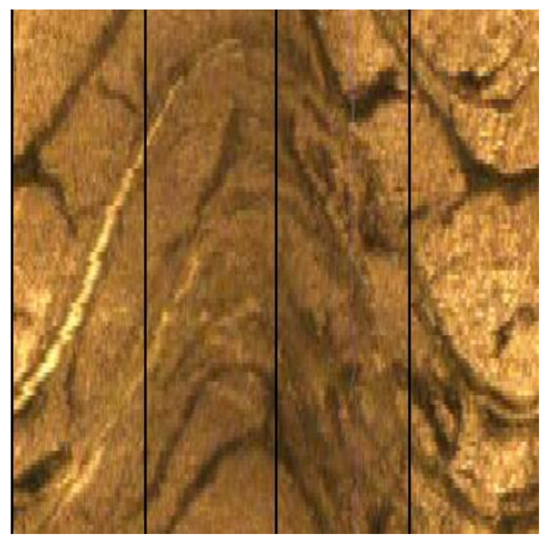
Optical Televiewer





Optical Televiewer

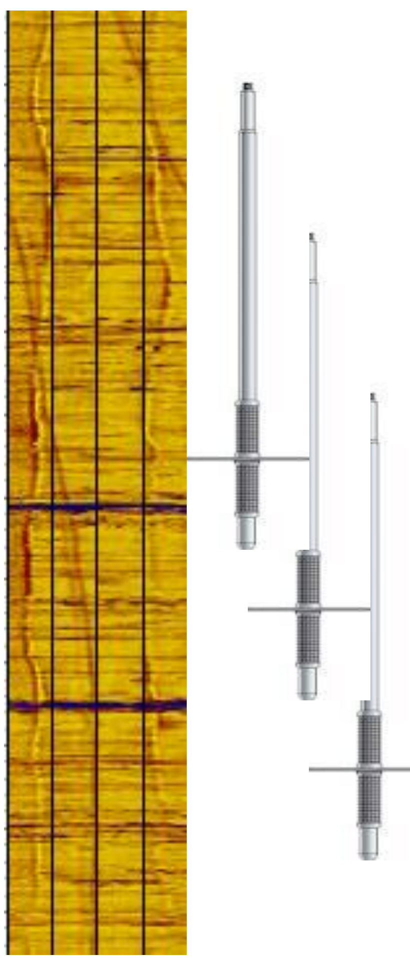
Large Bedding Plane Fracture at 270’

Bedding Plane Fracture @ 177.5’

Steeply-Dipping Mineralized Fractures @ 65’ to 67’

HPFM Testing to Support Estimation of Transmissivity and Hydraulic Head

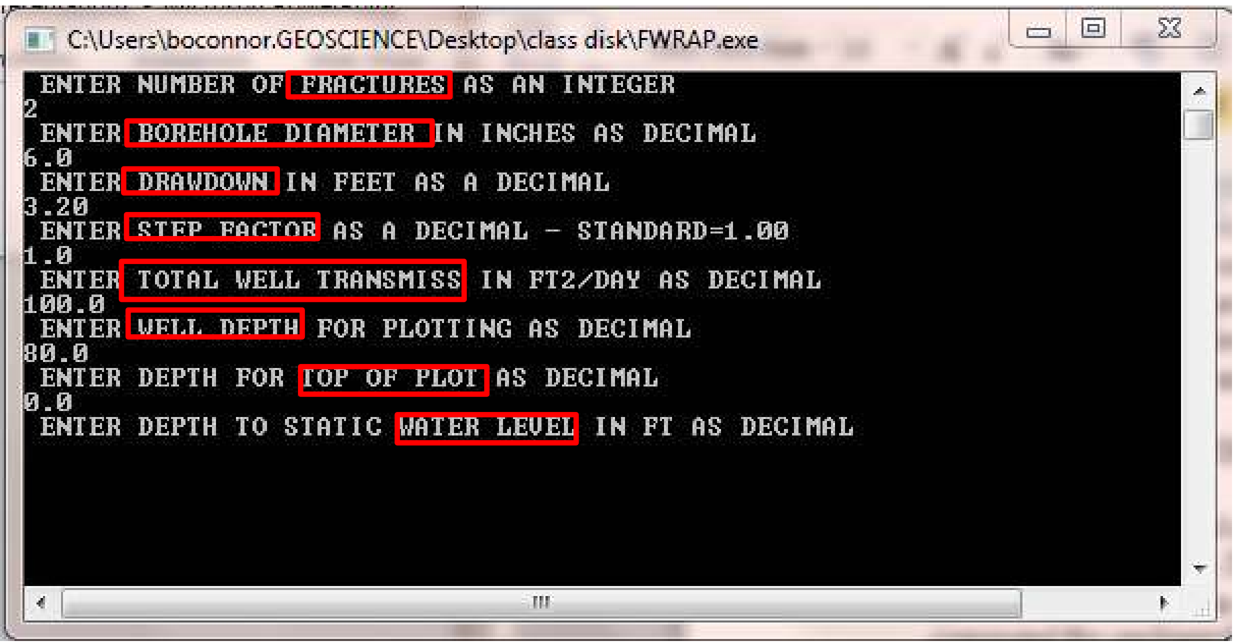
Field Procedures



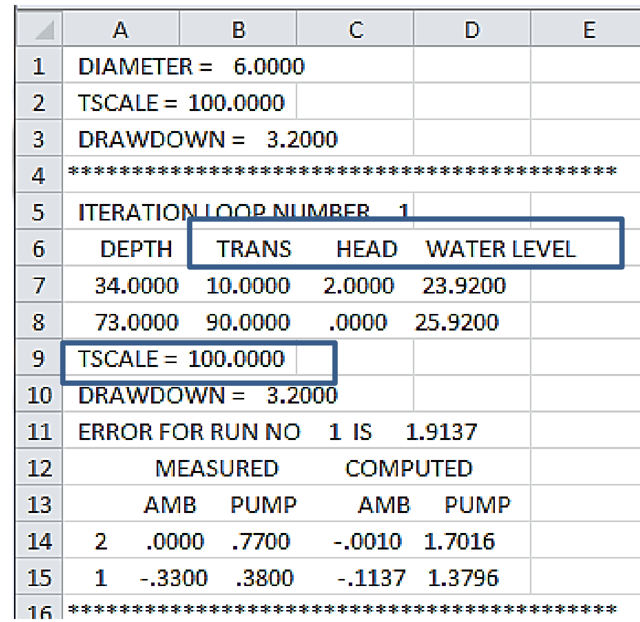
Data Analysis

- Interpret variation in flowmeter data collected in field
- Identify ambient and pumped flow rate above each zone / fracture
- Forward model head difference driving flow and zone transmissivity using FWRAP or FLASH model

FWRAP iterations provide hydraulic background



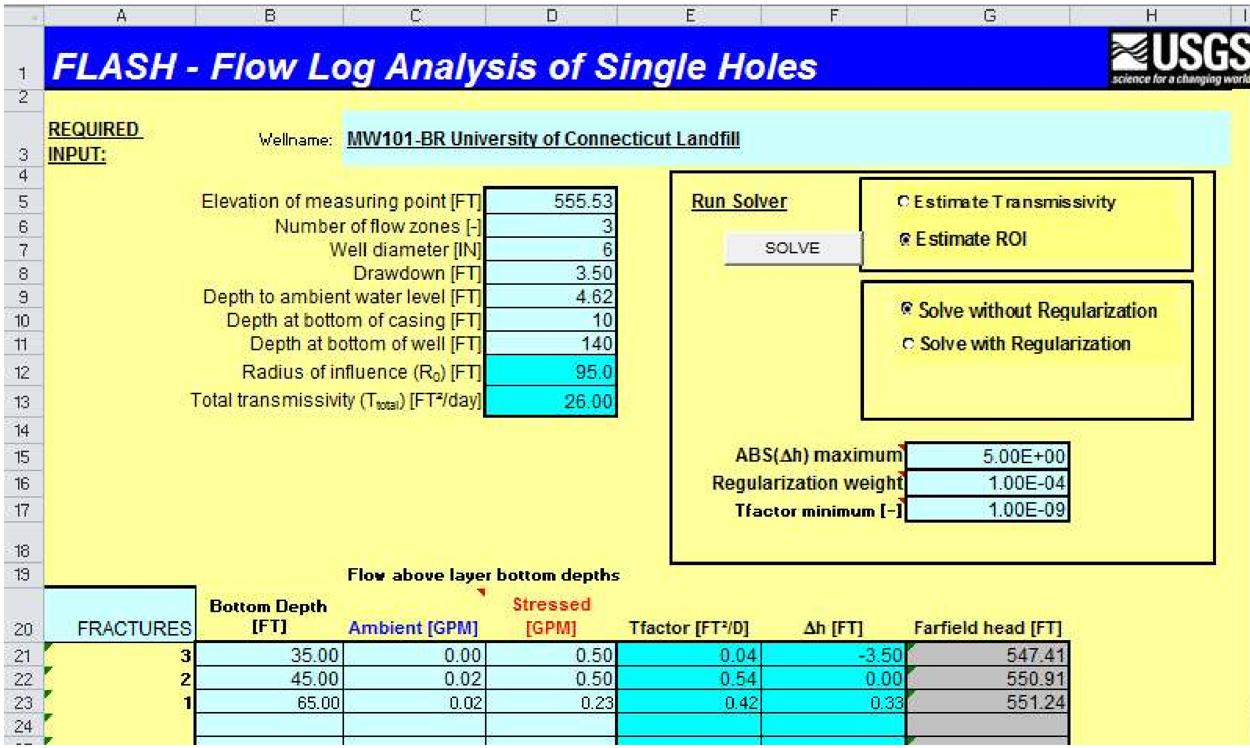
a. A sample run of F. Paillet's FWRAP Model



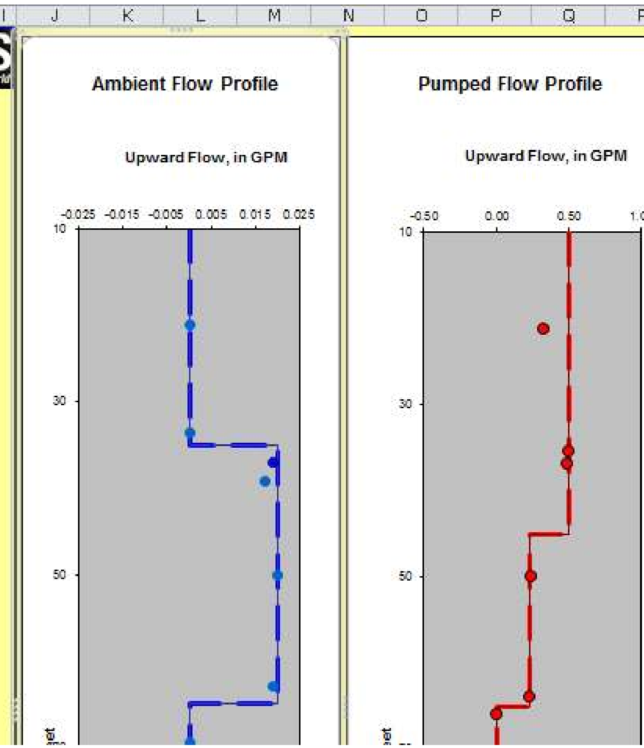
b. Excel Output of FWRAP Model

(Paillet, 1998)

FLASH solver helpful in studying highly fractured environments



a. FLASH Excel Inputs Sheet

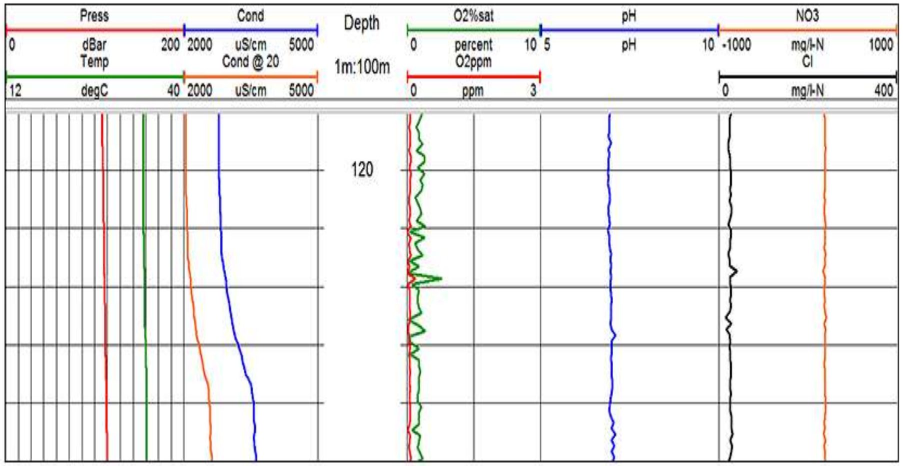


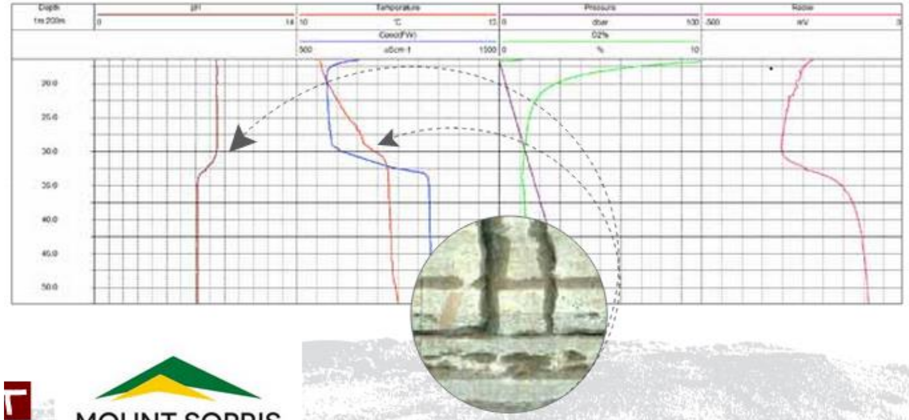
b. FLASH Excel Output Profiles

(Day-Lewis et al., 2011)

Water Quality Logs

- Discrete depth sampler for grab sampling at inflow zones
- Trolling multi-parameter water quality probe measures:
  - Pressure
  - Temperature
  - Fluid conductivity
  - pH
  - Dissolved oxygen
  - Oxidation-reduction
  - Single ion (e.g., Nitrate, Ammonia, Chloride)
- Assess geochemistry for:
  - Natural metals GW impact
  - Changes due to in-situ treatments

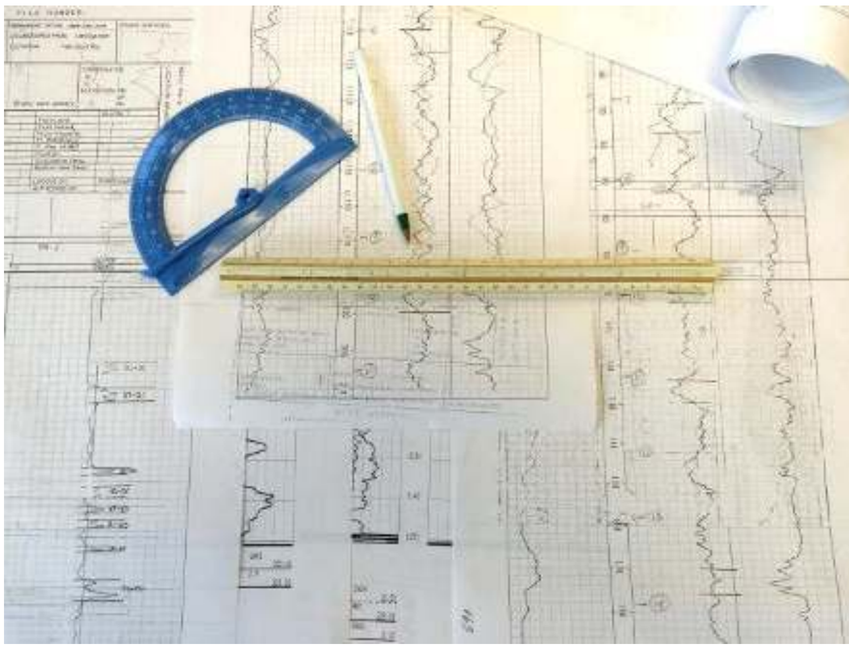


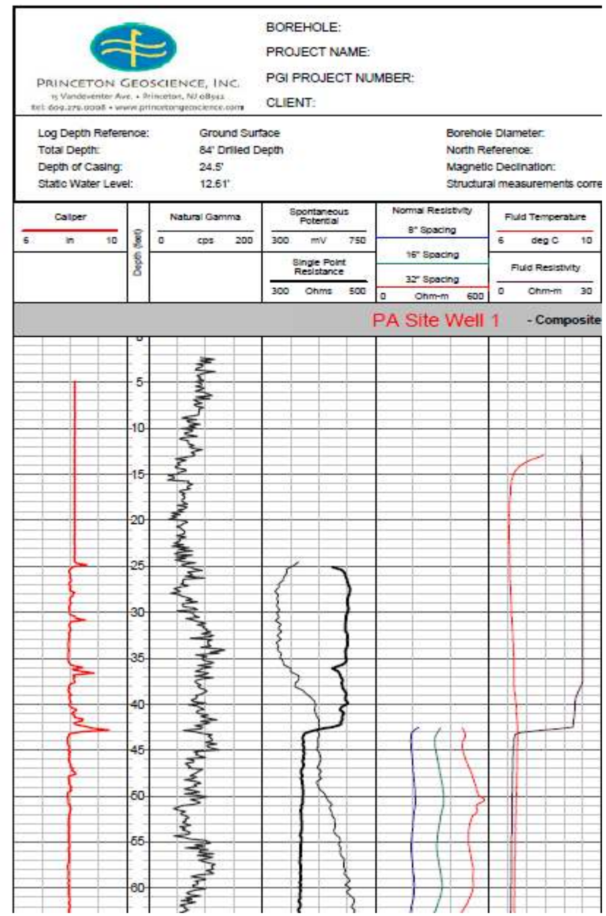


MOUNT SOPRIS
INSTRUMENTS

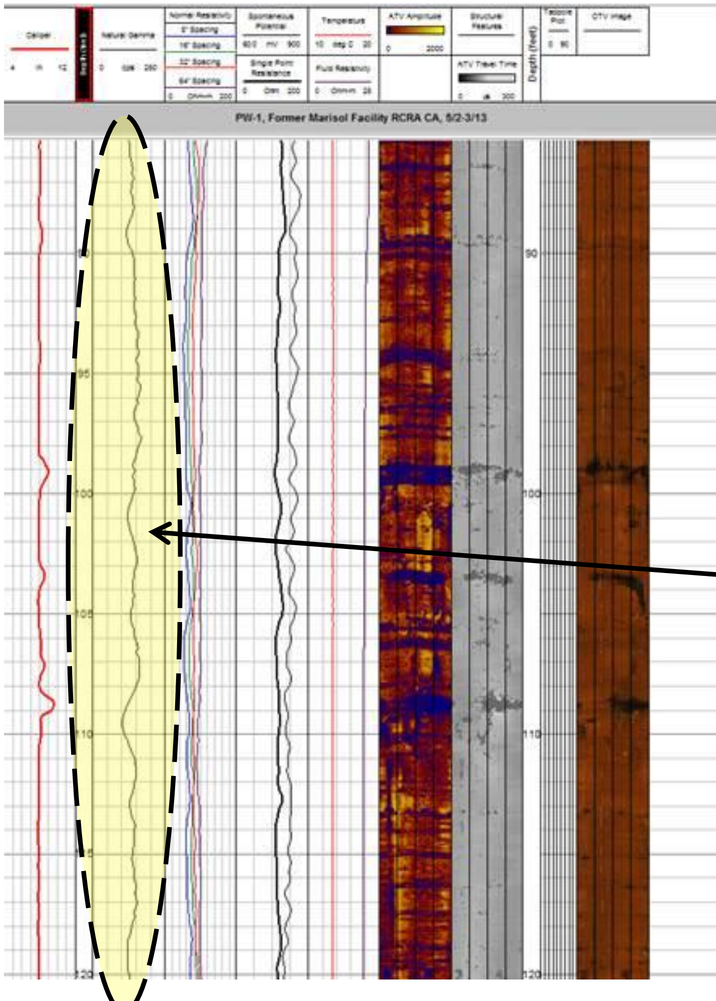
Related Data Management

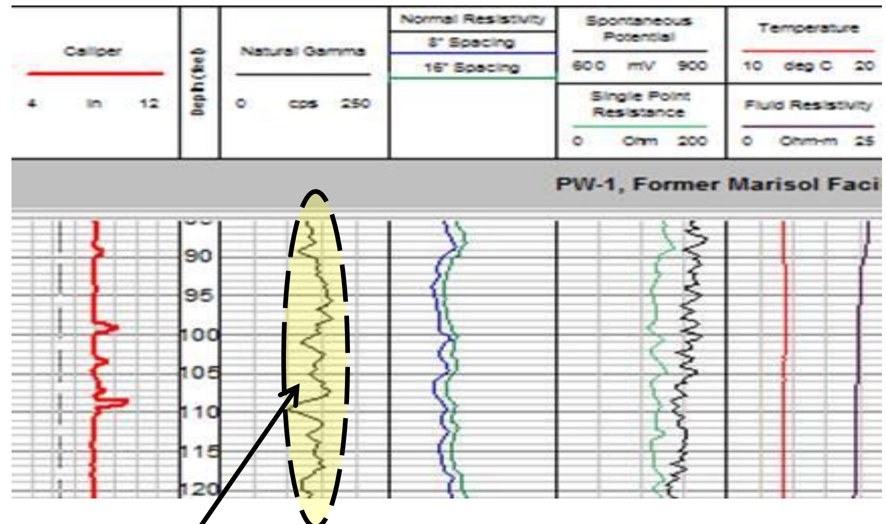
Legacy Data Revival





Appropriate Scaling Assists Correlation





Same well and depth interval

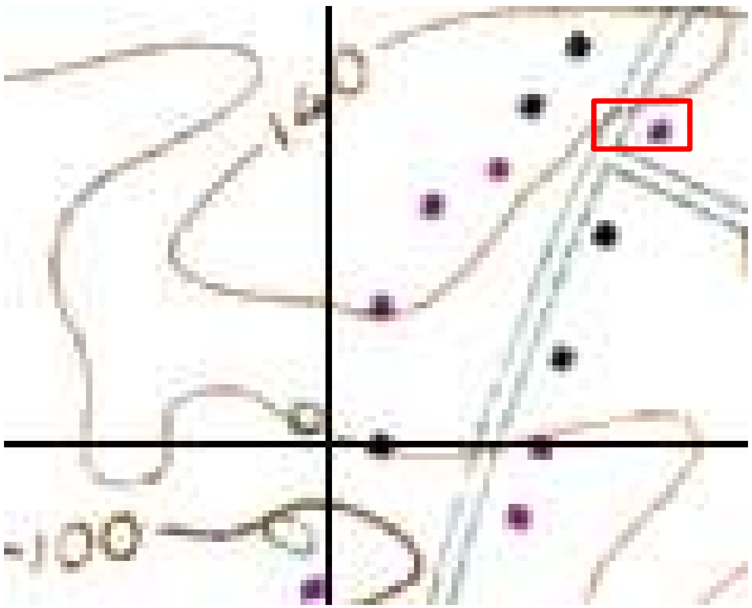
Expanded scale good for composite plots, but gamma features vague

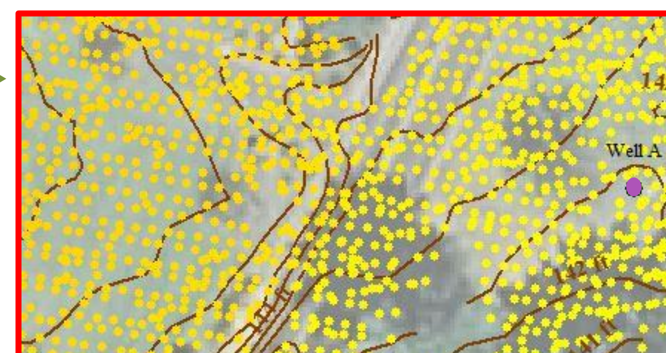
Need to “crunch” the scale vertically to bring out contrast for correlating logs from hole to hole.

...Related Data Management

LIDAR-based Topographic Mapping

USGS 20 FT Contours





Contours generated by LIDAR point cloud data

...Related Data Management

LIDAR-based Topographic Mapping

Topographic Contours generated in LIDAR point cloud data, used in concert with bedrock structural data (contoured bedding or fracture elevations) – predict depth to zone of interest:

Subtract structural elevation of fracture or bed from LIDAR based ground surface elevation (e.g., at proposed drilling location)