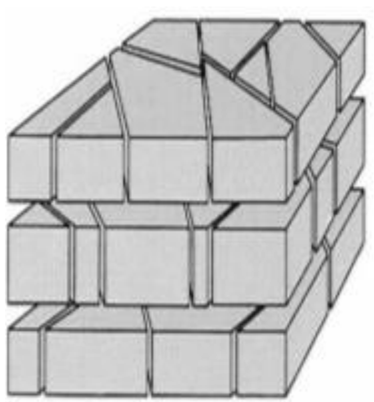
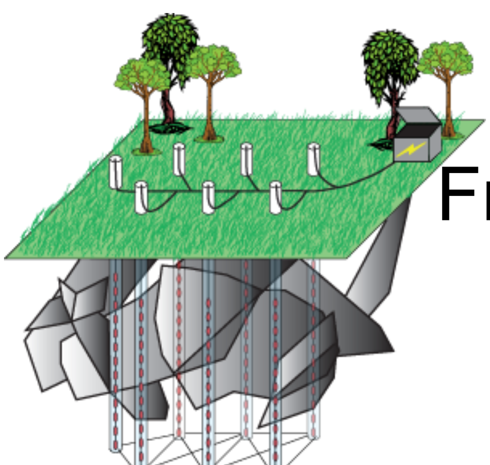
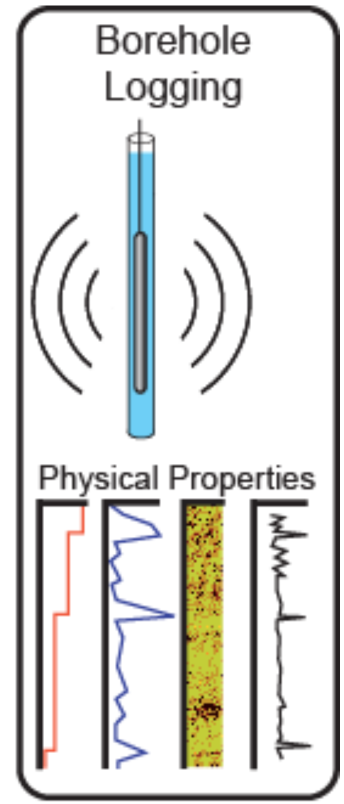
Borehole Geophysics for Fractured Rock

EPA Region 10 Workshop
September 11-12, 2019



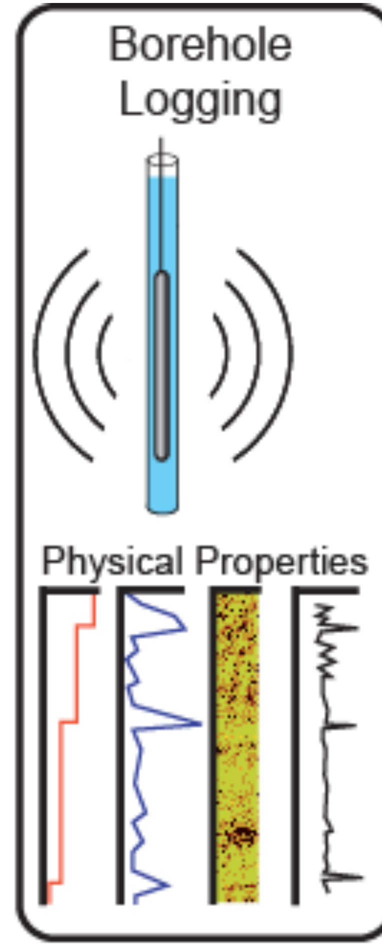


Frederick Day-Lewis, USGS
Carole Johnson, USGS



Borehole Geophysical Logging Outline

- Motivation
- Tools for characterizing:
  - well construction,
  - geology,
  - fractures,
  - hydrology/hydraulics
- Selected Tools
- New Tools
- Examples in fractured rock



Purpose for borehole geophysics at contaminated sites

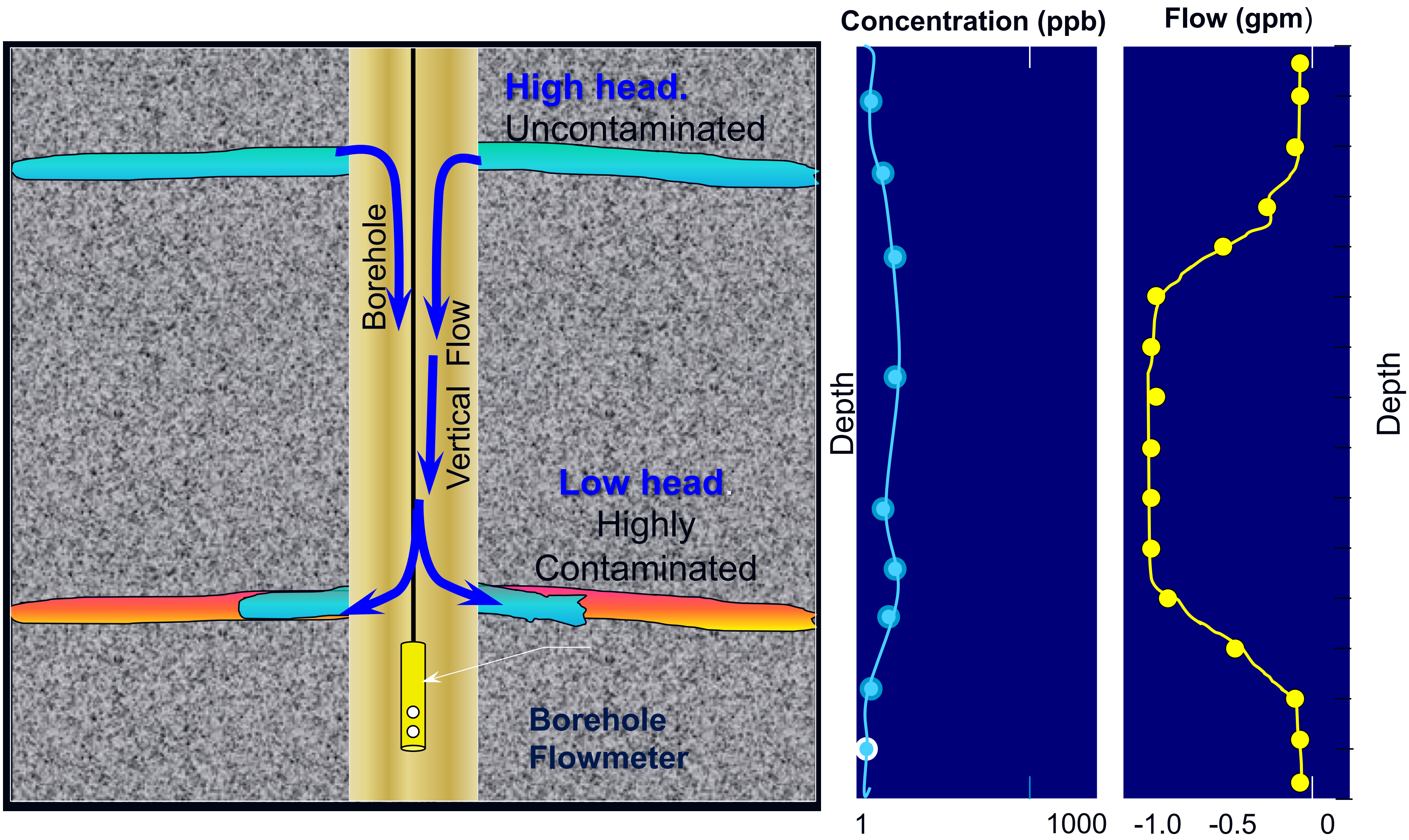
Borehole geophysics can help with goals:

- obtain meaningful water-quality samples
- complete boreholes for purposes of sampling and preventing cross contamination
- understand how contaminants might move through your fractured rock site
- plan additional geophysical, monitoring and hydraulic tests

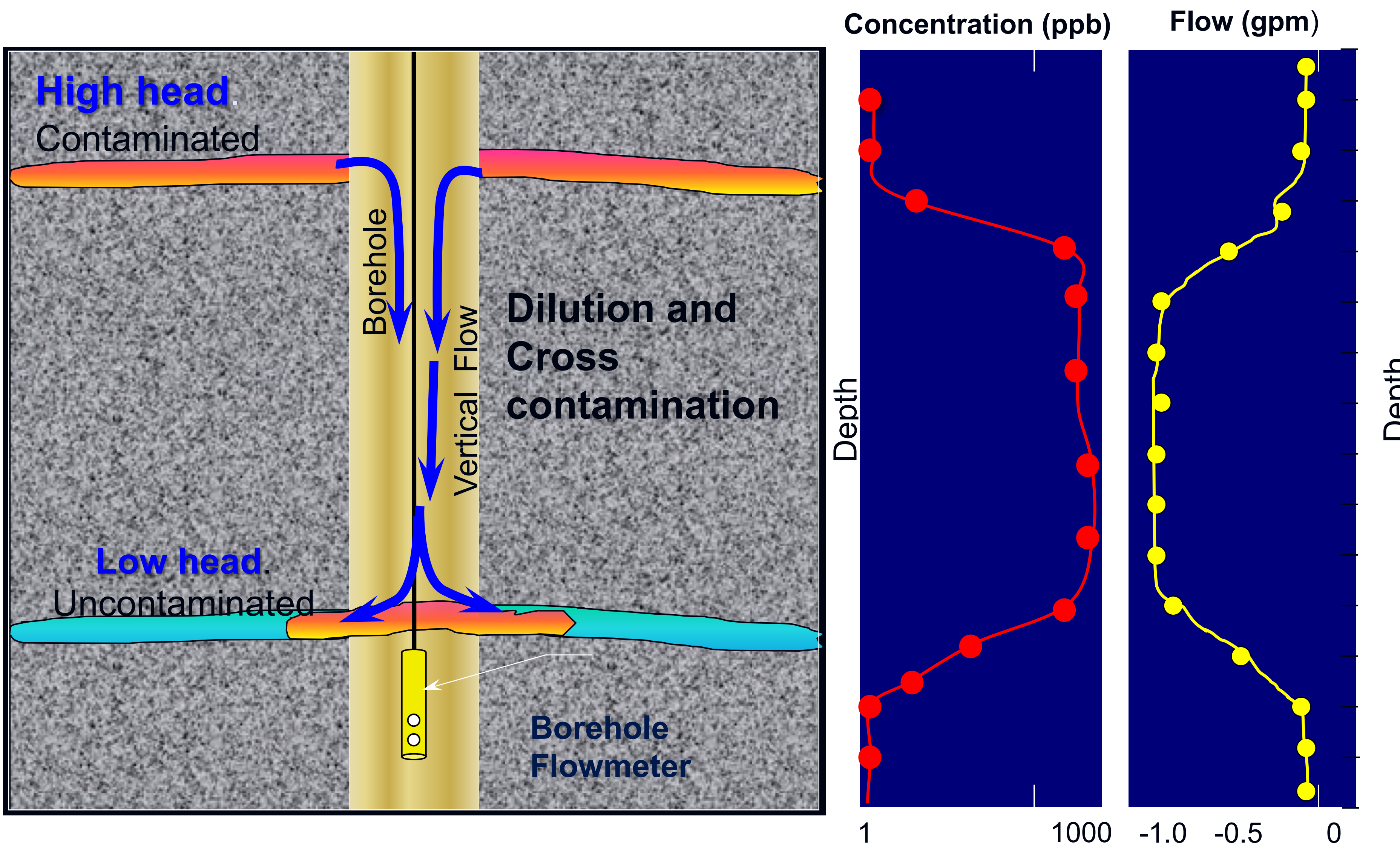
Motivation: A frequent problem is sampling in open-hole wells…

"Water-quality samples collected from boreholes with long open intervals can be interpreted incorrectly if hydraulics of the aquifer and borehole are not taken into account"…. leading to erroneous interpretation of water-quality data, wasted effort, and wasted resources.

Schematic: vertical flow and significance for sampling Scenario 1



Schematic: vertical flow and significance for sampling – Scenario 2



Borehole Geophysical Methods

Used to Characterize:

1. Well construction and integrity of the borehole
2. Geology and structure
3. Water (amount and chemistry)
4. Hydraulically active fractures intersecting boreholes and between boreholes

Tool selection should be targeted for project needs.
This talk summarizes selected methods.

1. Borehole construction and integrity

- Three arm caliper – borehole diameter identifies constrictions and enlargements

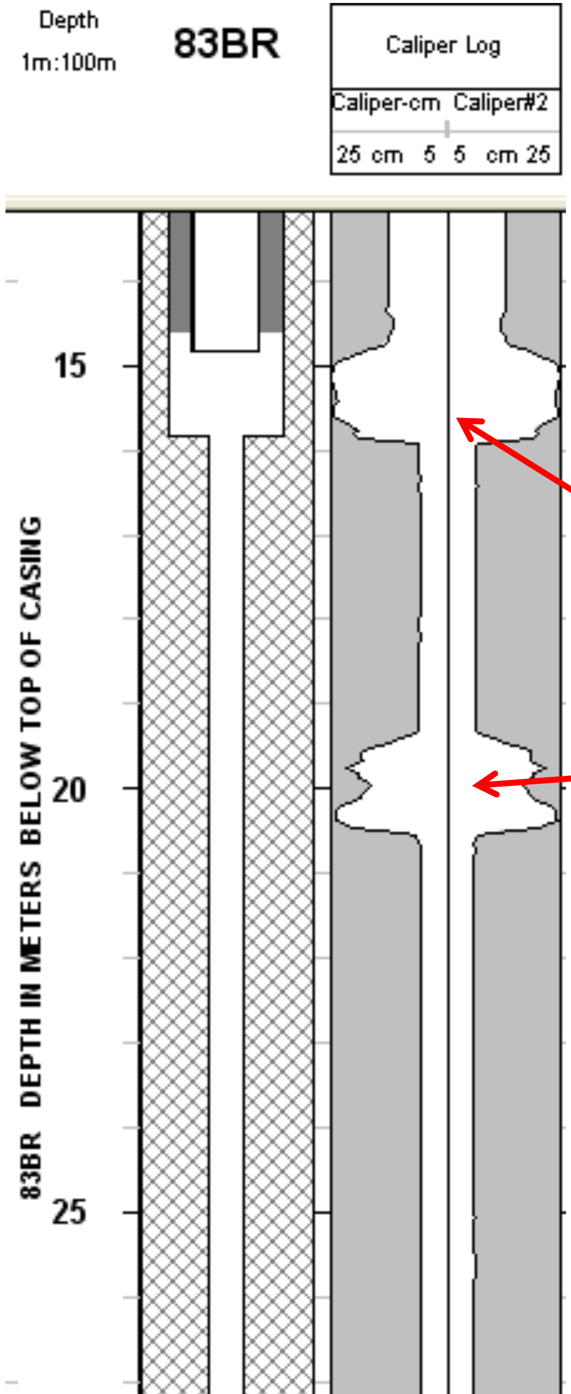
- Electromagnetic Induction
  often to find bottom of steel casing

- Imaging tools – cracked casing, bottom of casing, construction, etc

- Deviation (x, y, z -- true vertical depth)

These tools are particularly helpful for “unknown” boreholes.

Caliper Log



Here the caliper log is shown with shading to help visualize enlargements and constrictions in the borehole.

15 m we have an enlargement associated with construction

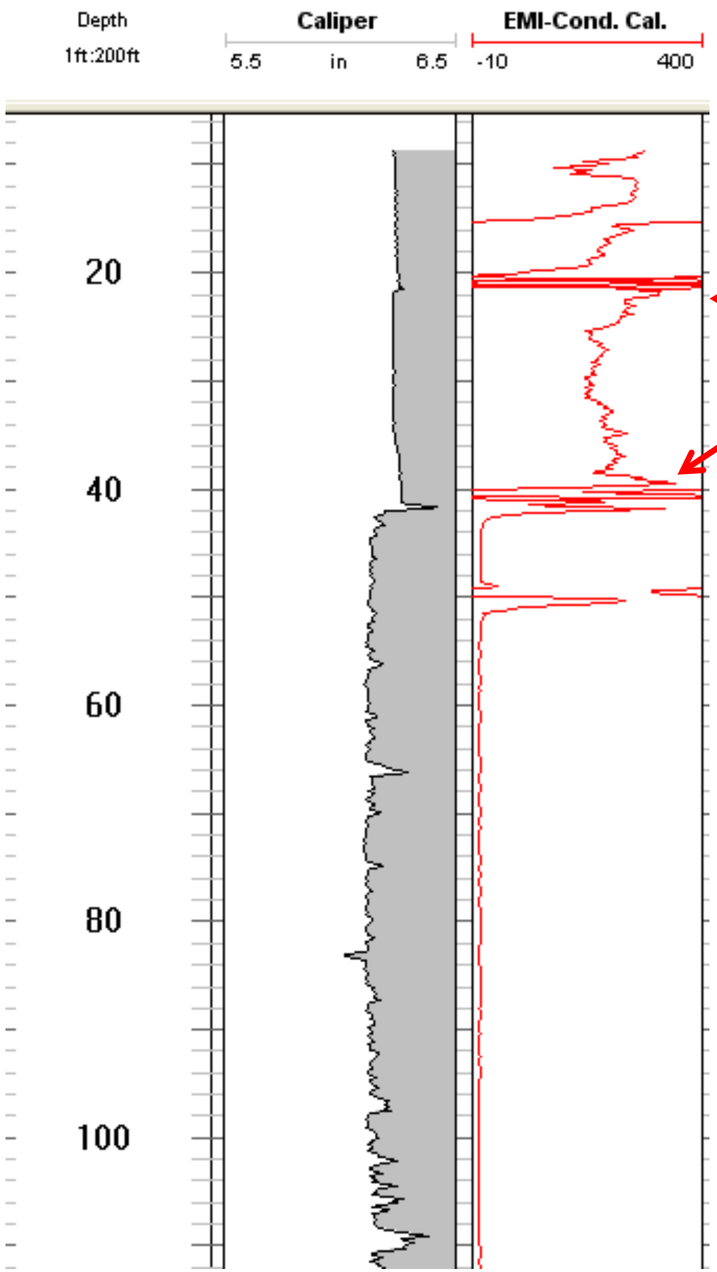
20 m we have an elaragement likely caused by a fracture.

Important to calibrate the caliper tool so that exact measurements can be used in advance of other equipment and tools to be lowered into the borehole.

Electromagnetic Induction (EMI)

- Measures the bulk electrical conductivity of the rocks and the fluids in the rocks surrounding the borehole
- Changes in electrical conductivity are caused by variations in porosity, borehole diameter, TDS in formation fluid, and metallic minerals
- Most useful in delineating bottom of steel casing, lithology changes, and electrical properties of water in the formation around the borehole (i.e. saline and fresh water)
- Cannot sample through steel casing
- Most sensitive to bedrock and pore water approximately 1 ft from the probe

Example EMI Log

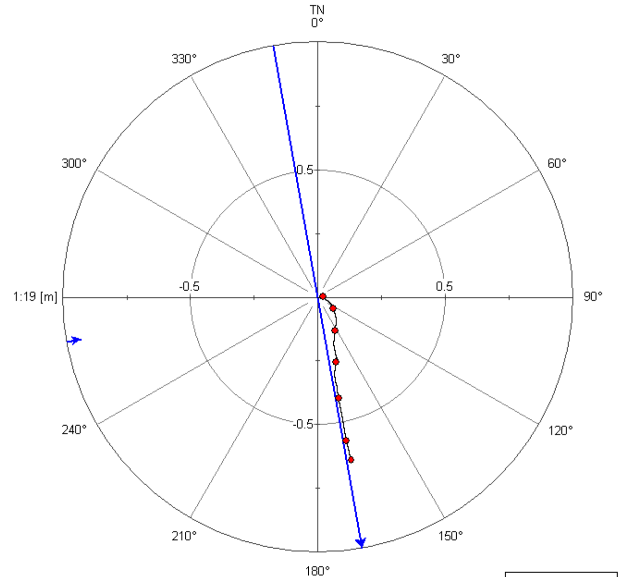


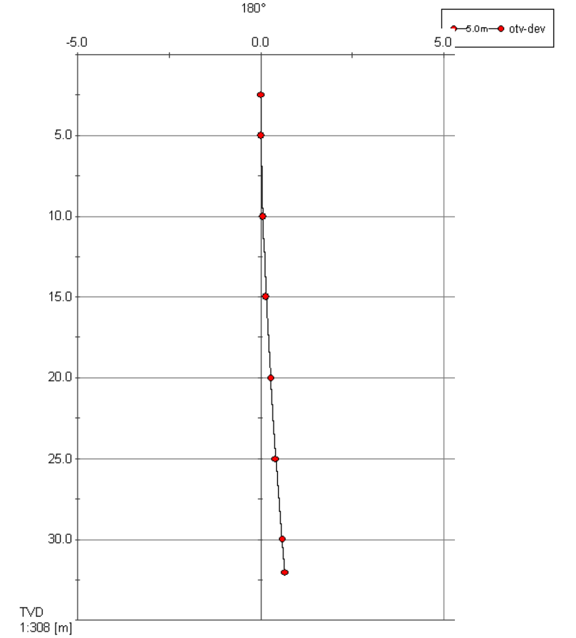
- EMI shows joints in the casing and the bottom of casing
- Bedrock is low conductivity (schist)

Identifying the base of casing is sometimes important to sort out leakage from casing or fracture

Deviation

- Dip and Dip Azimuth are measured usually at 0.1ft increments
- Processing converts values to x, y, z and true vertical depth
- Some boreholes are badly deviated and can cause problems with other tests
- Needed for hole-to-hole radar and for correcting oriented image data





2. Characterize the geology/framework

Lithology

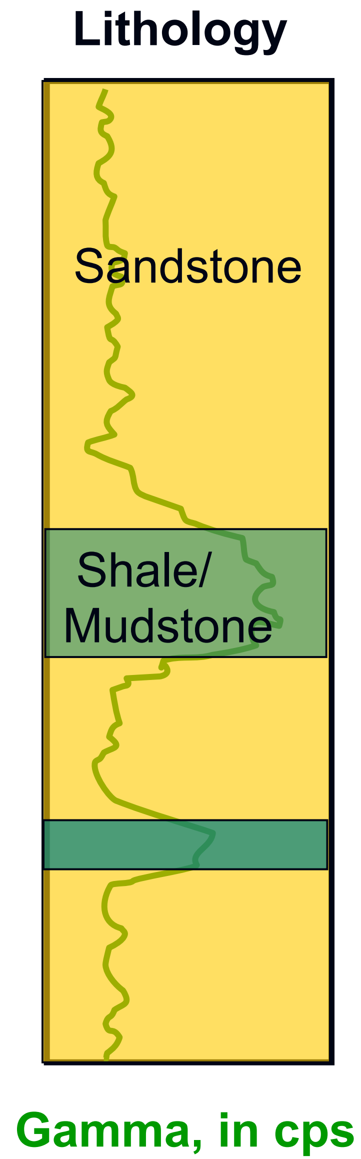
- Gamma
- Electromagnetic induction (as shown)
- Resistivity (LS-N, SPR, Induced Polarization)
- Acoustic reflectivity (derivative of ATV image)

Fractures and structures

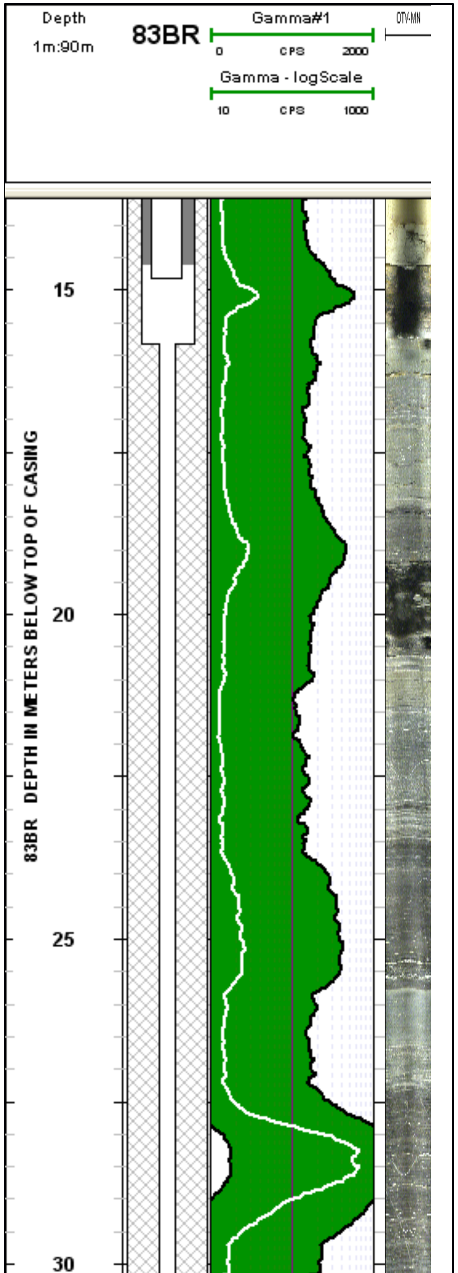
- ATV and OTV imaging, Caliper

Gamma Tool

- Measures total gamma radiation, which caused by decay of naturally occuring K^{40}, U, and Th.
- Counts (in CPS or APIu) can be related to lithology
- Typical vertical resolution is 1 to 2 feet
- Can be used in:
    - Air-, water-, or mud-filled boreholes
    - Open, PVC, or steel cased boreholes



Borehole logs put into a larger-scale context



Light Gray
Massive

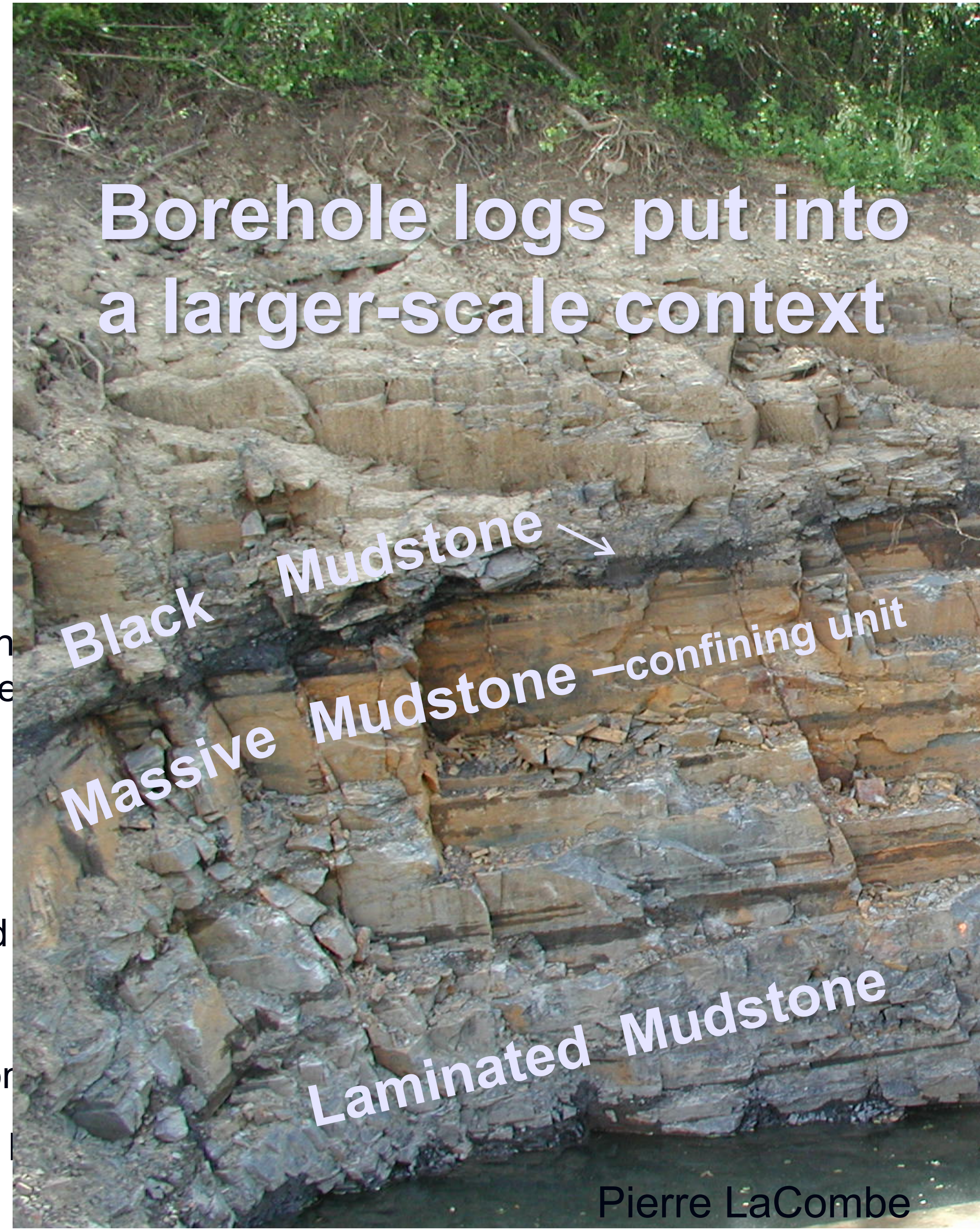
Black Carbon
Mudstone

Light Gray
Massive

Dark Gray
Laminated

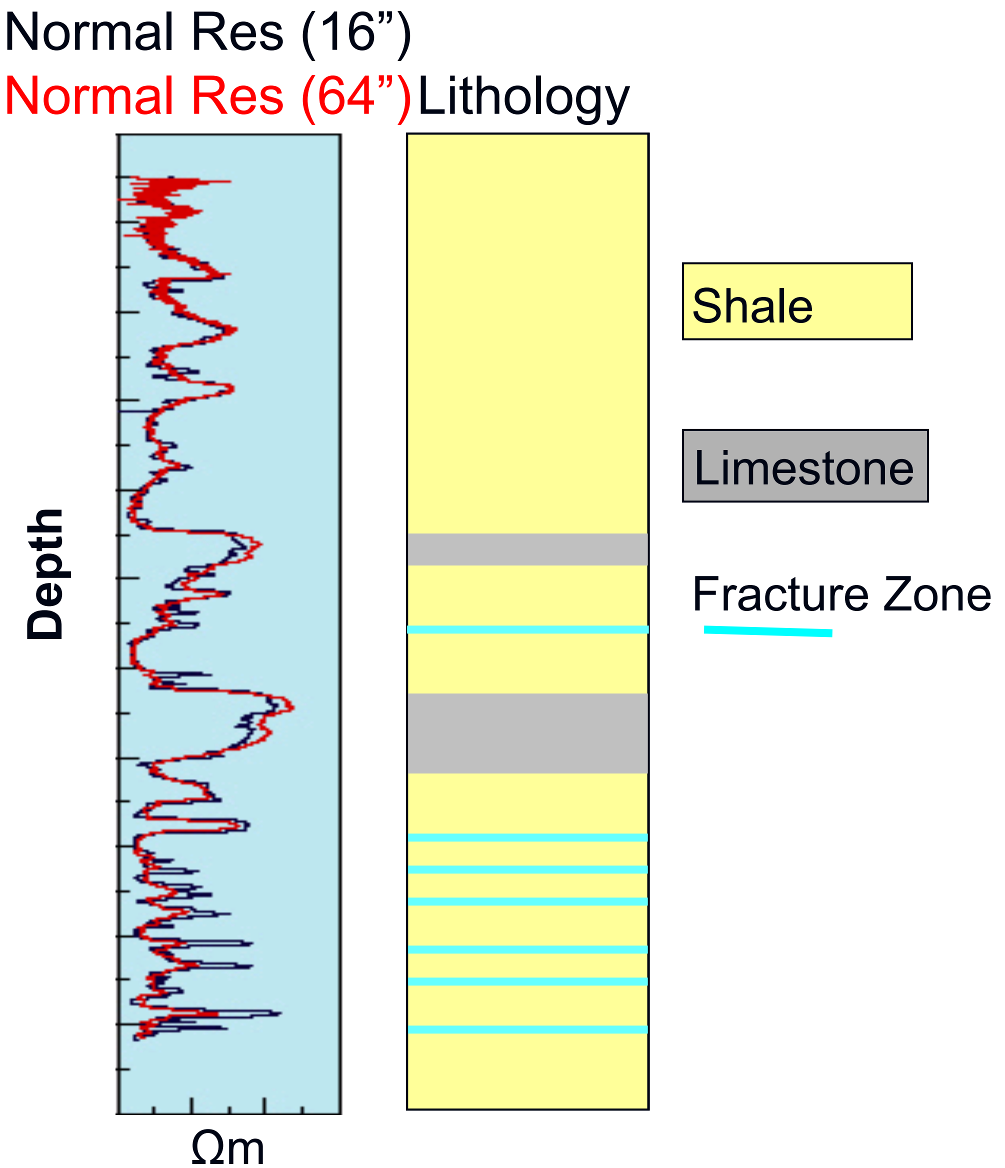
Black Carbon

Dark Gray



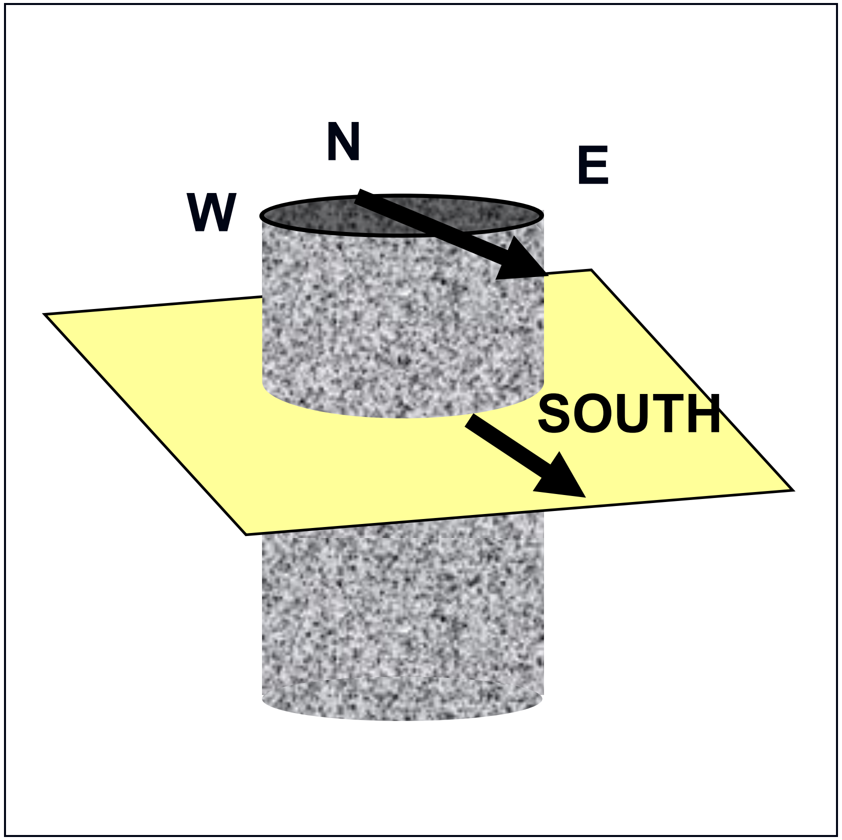
Long- and Short-Normal Resistivity Data

- Measures resistivity of borehole fluid and formation surrounding the borehole
- Long (64-in) and Short(16-in) measurements (now also 8, and 32-in)
- Characterize lithology, and fractures/water quality

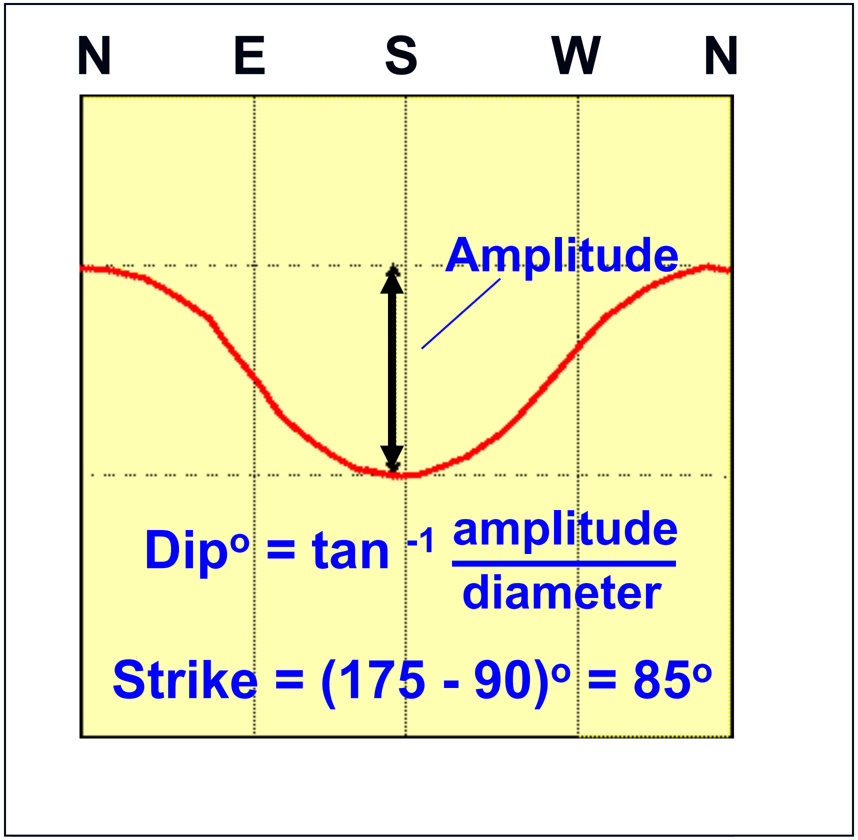


Borehole Imaging

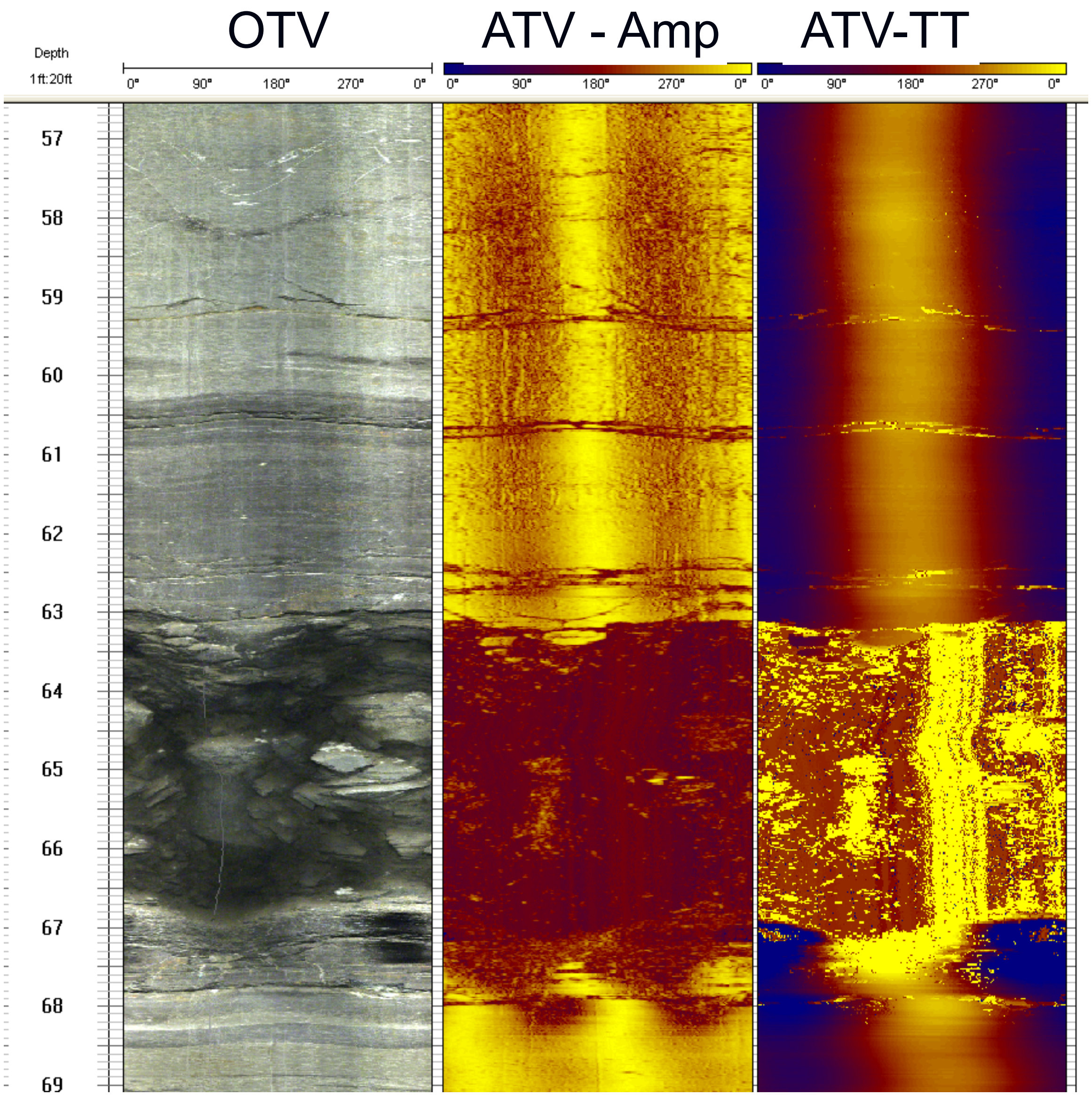
3-D wrapped image



Projected image



Borehole Imaging- Optical and Acoustic



To identify stratigraphy

and determine

depth and orientation of fractures and bedding planes

Side by side comparisons, interpretations, and display data

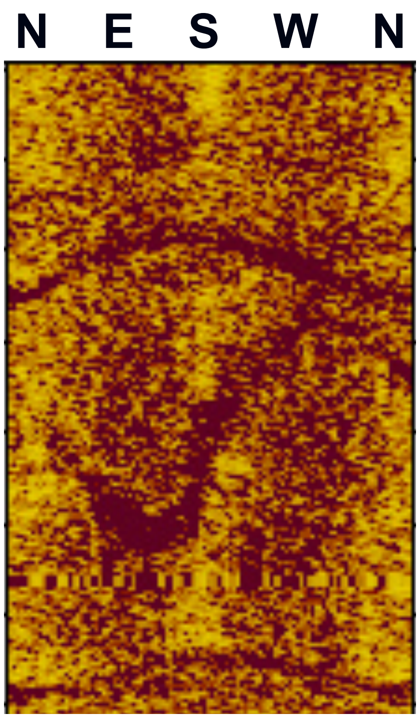
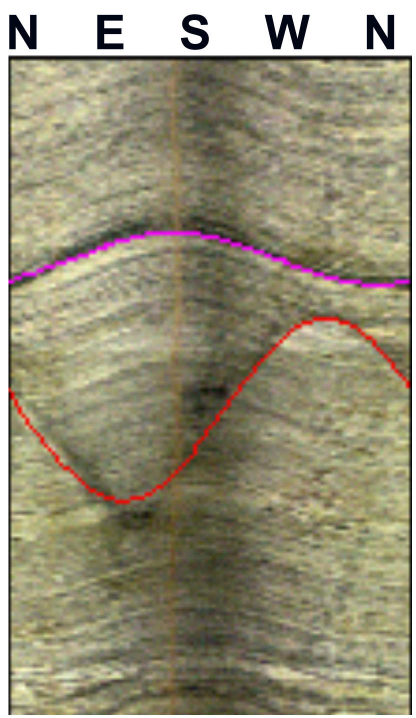
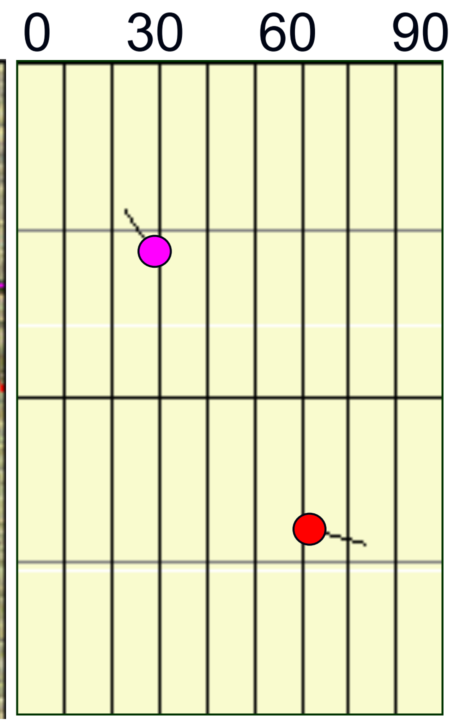


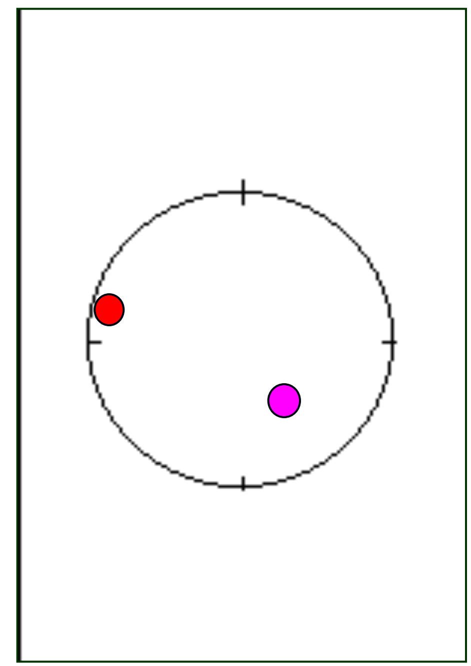
Image Plot

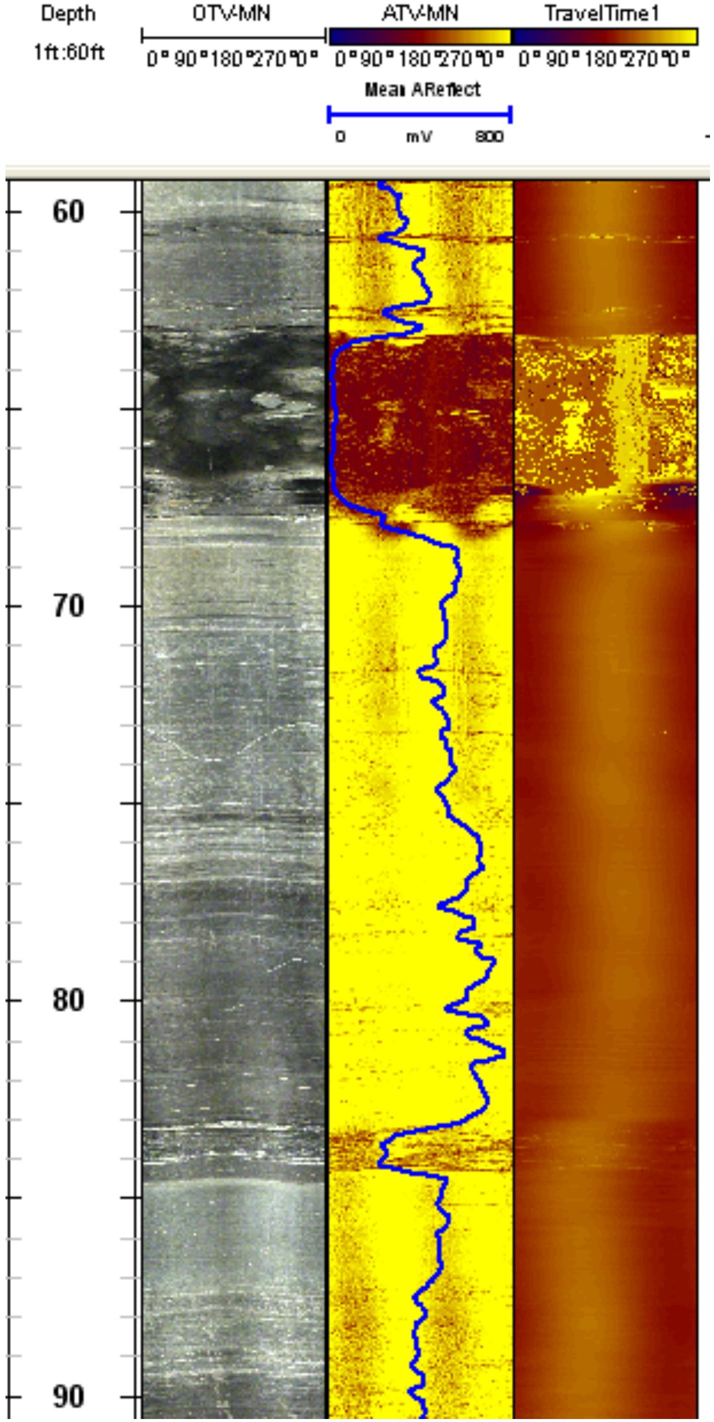


Projection Plot



Tadpole Plot


Stereographic Projection



Acoustic Reflectivity Log

Using the ATV image take the median or the average acoustic reflectivity for each depth (0.02 ft) for all 360 degrees of the borehole

Log in blue – shows the relative hardness of the borehole wall, which relates to the rock type

3. **Methods to characterize fluids**

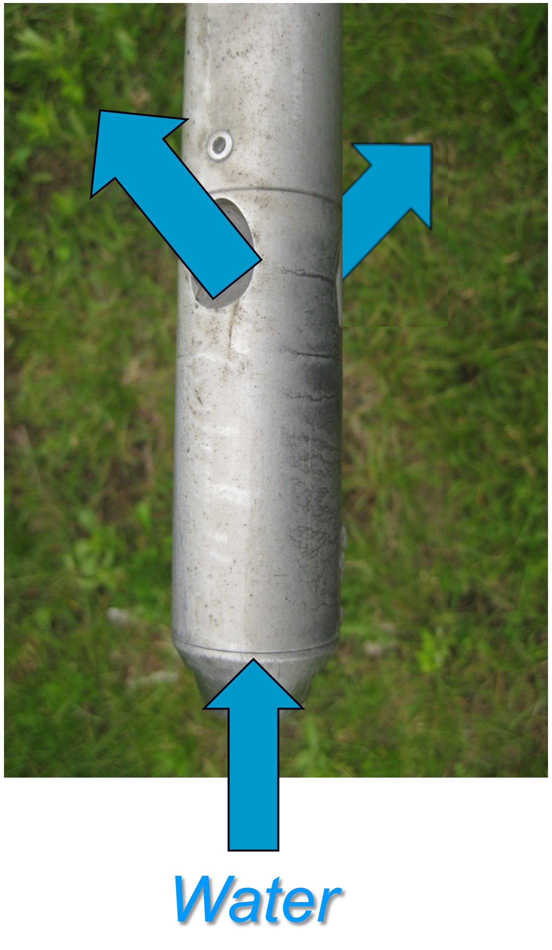
Chemistry of fluids in borehole and formation:

- Fluid electrical conductivity (FEC) and temperature of fluids in the borehole and
- Electromagnetic induction (EMI) and
- Normal resistivity for fluids in the formation

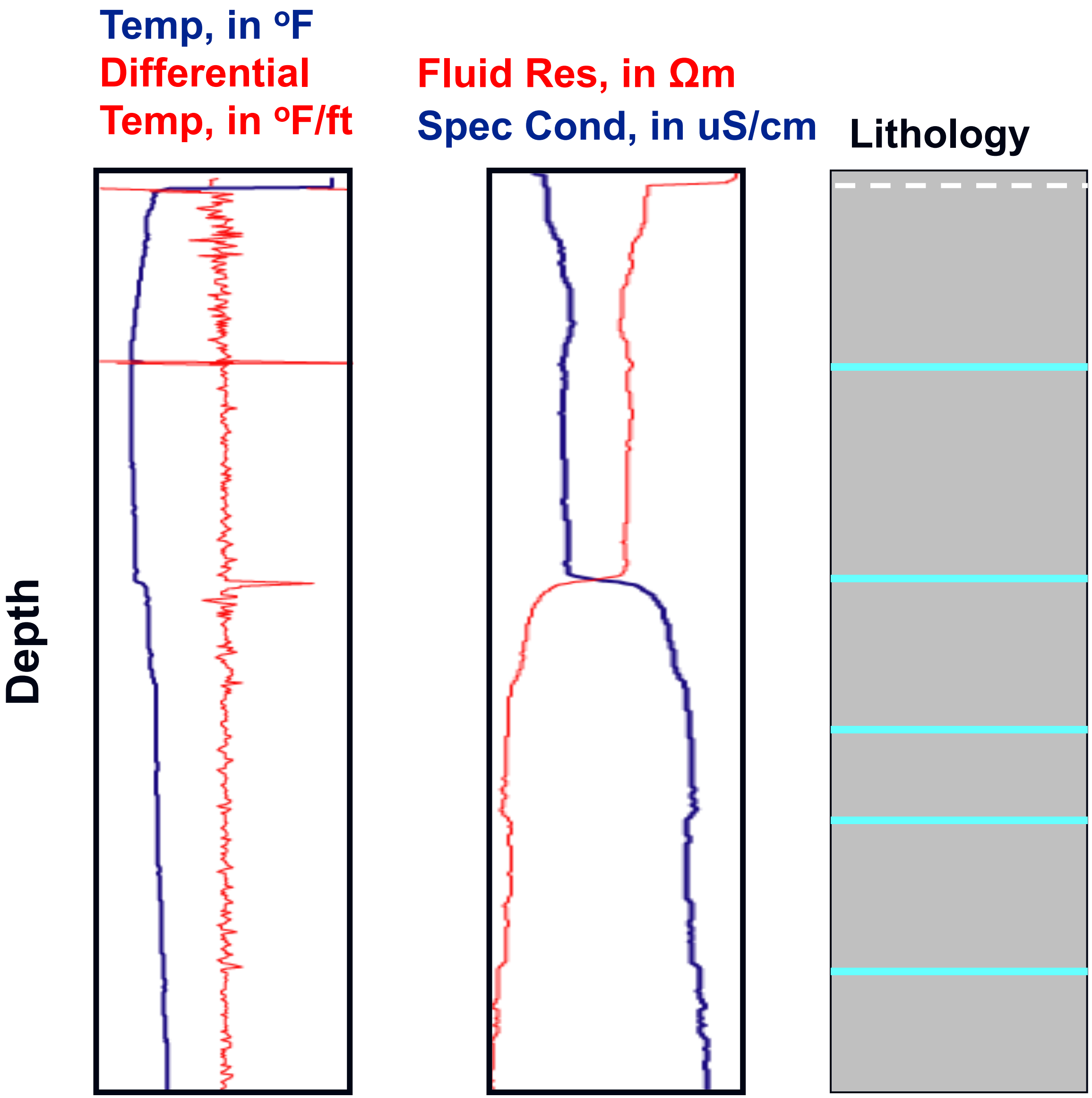
- Differencing these logs over time to identify changes in the aquifer over time.

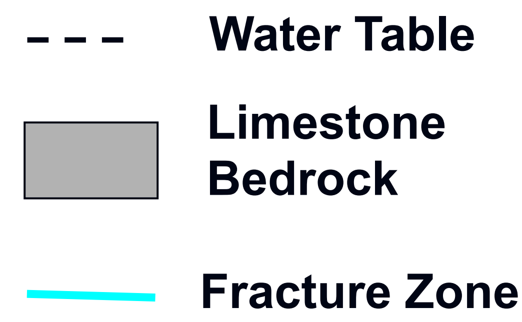
Fluid Electrical Conductivity (FEC)

- Single tool contains a combination of sensors for temperature and resistivity of the fluid in the borehole
- **The fluid log is always run in the downward direction**, so that the water is channeled past the sensors on the bottom of the tool.
- Used to:
  - determine formations, fractures or zones with different water quality values (including effects of salinity, lithology, and contamination) and
  - identify where water enters (and/or) exits the borehole.



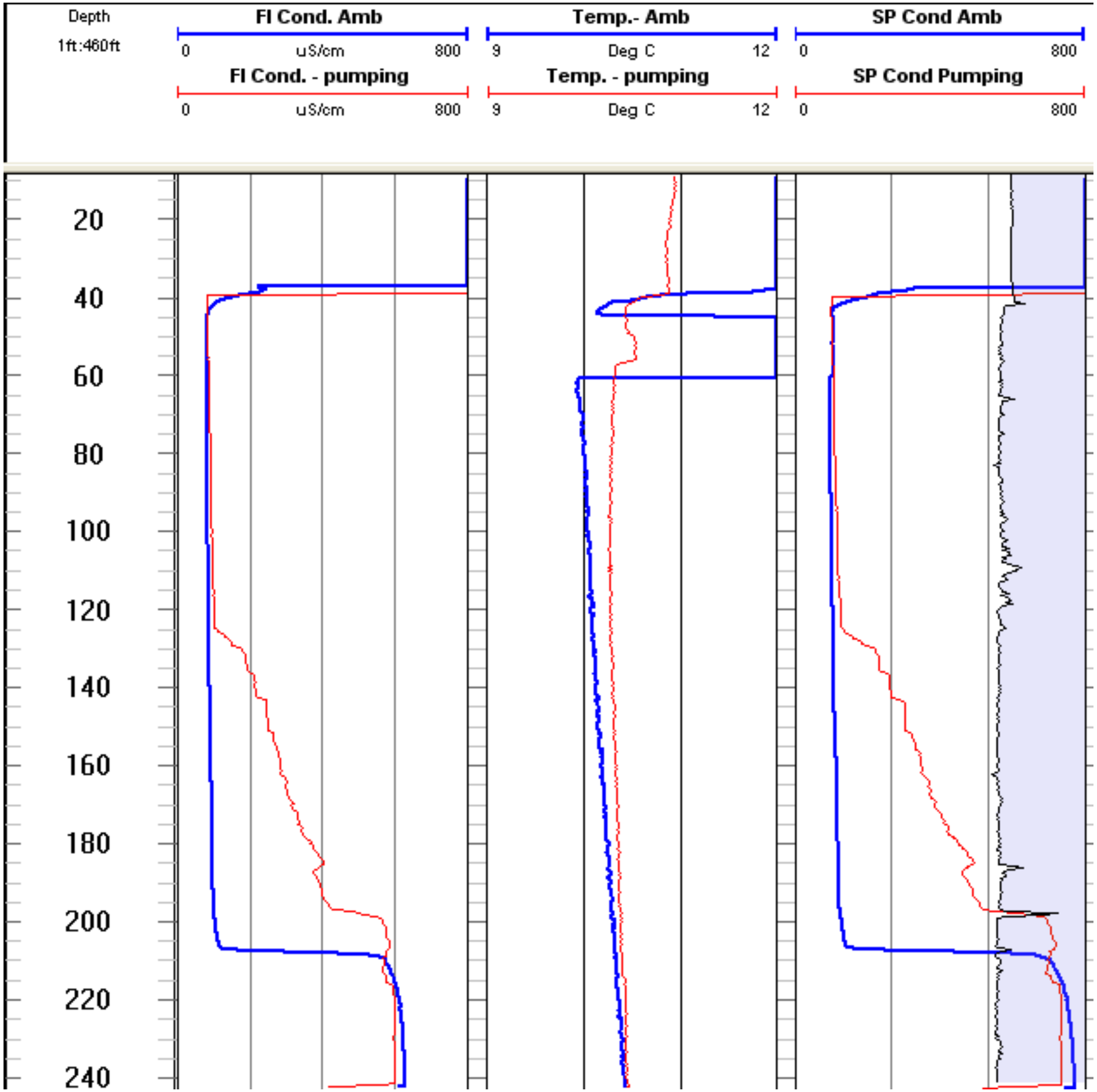
Fluid Resistivity Data





Same temperature over a long vertical interval may indicate vertical flow within borehole

Fluid Log Differencing



Vertical line segments of FEC logs suggest vertical flow

Before pumping and after pumping helps confirm inflow zones

Examples – to illustrate the combined strength of the logs

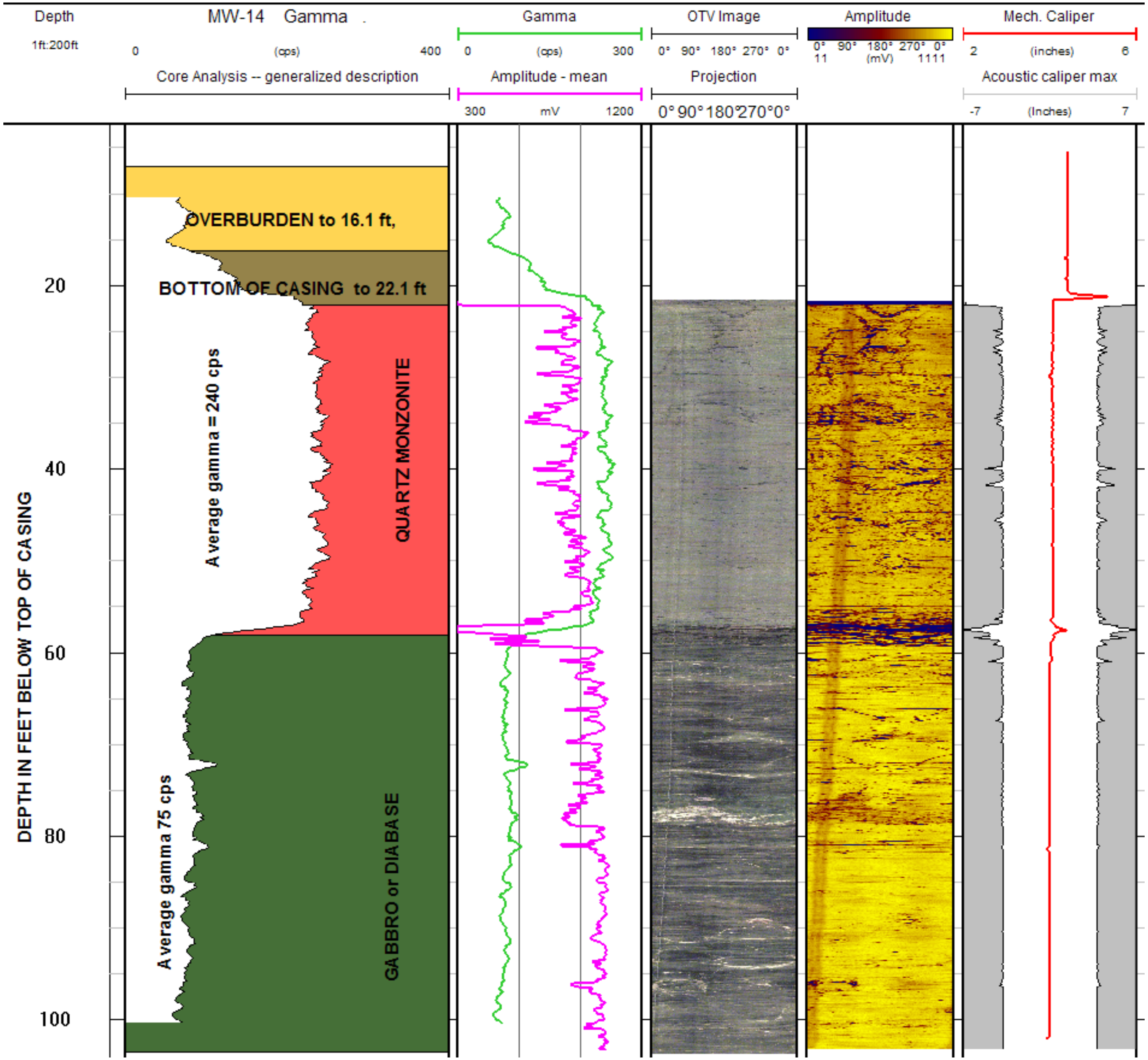
Combine and interpret together :

Crystalline – Igneous rock, Maine – example of correlating logs to lithology

Sandstone –California – example showing fracture orientation, rock types, and hydraulically active fractures

Mudstone – New Jersey – example showing correlation across several wells

EXAMPLE

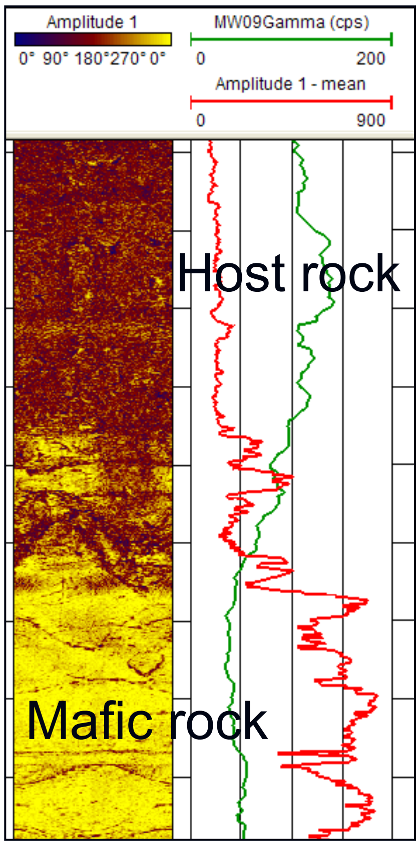


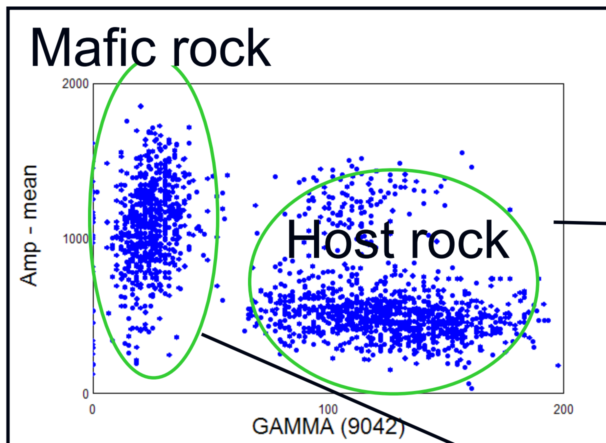
Machiasport, ME

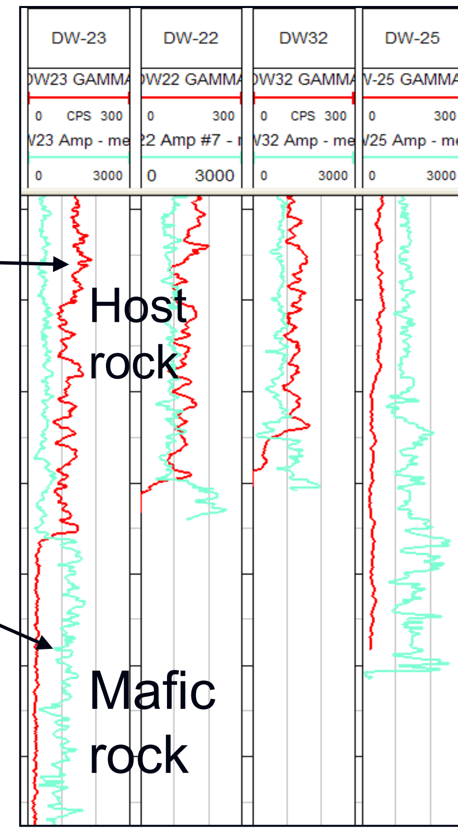
USGS SIR 5120

Combined Interpretation

Calculate acoustic reflectivity from ATV image; crossplot against gamma; establish relations; and use results to help interpret





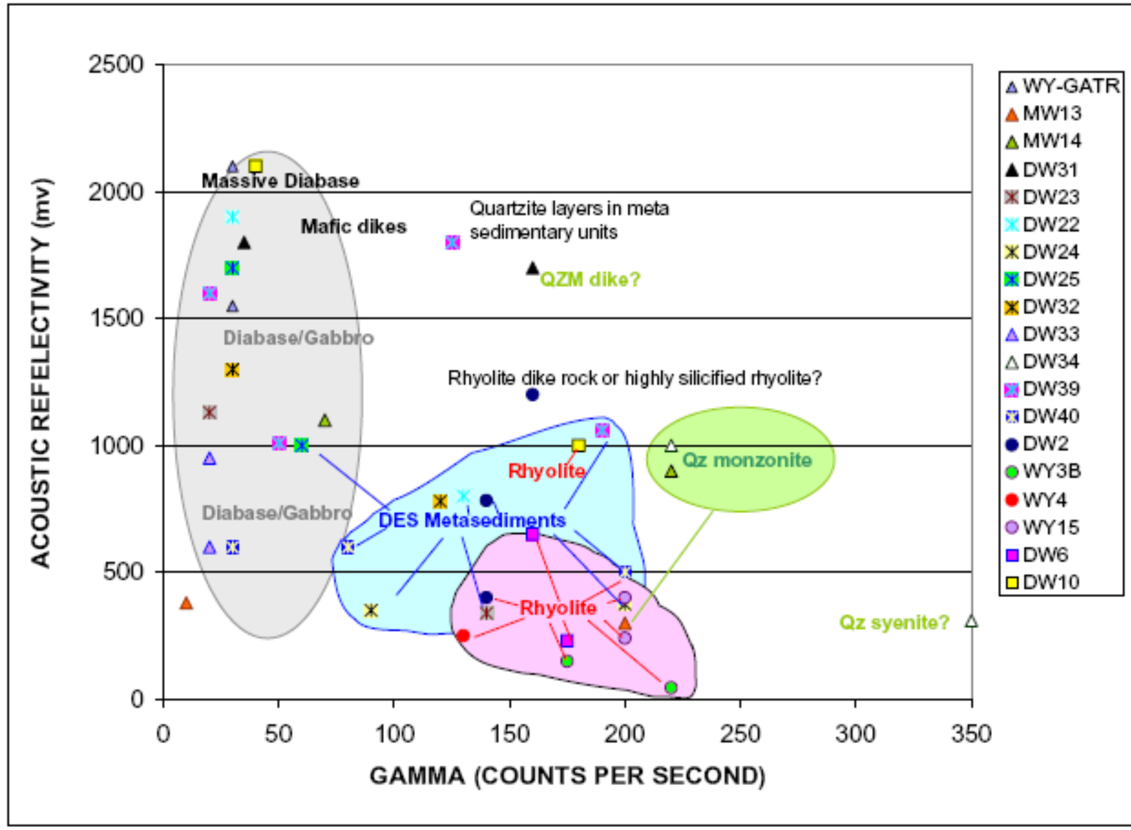


To help identify patterns within a single borehole – as seen here with amplitude ATV reflectivity and gamma logs

Bucks Harbor, Machiasport, ME

Establishing Lithologic Relations

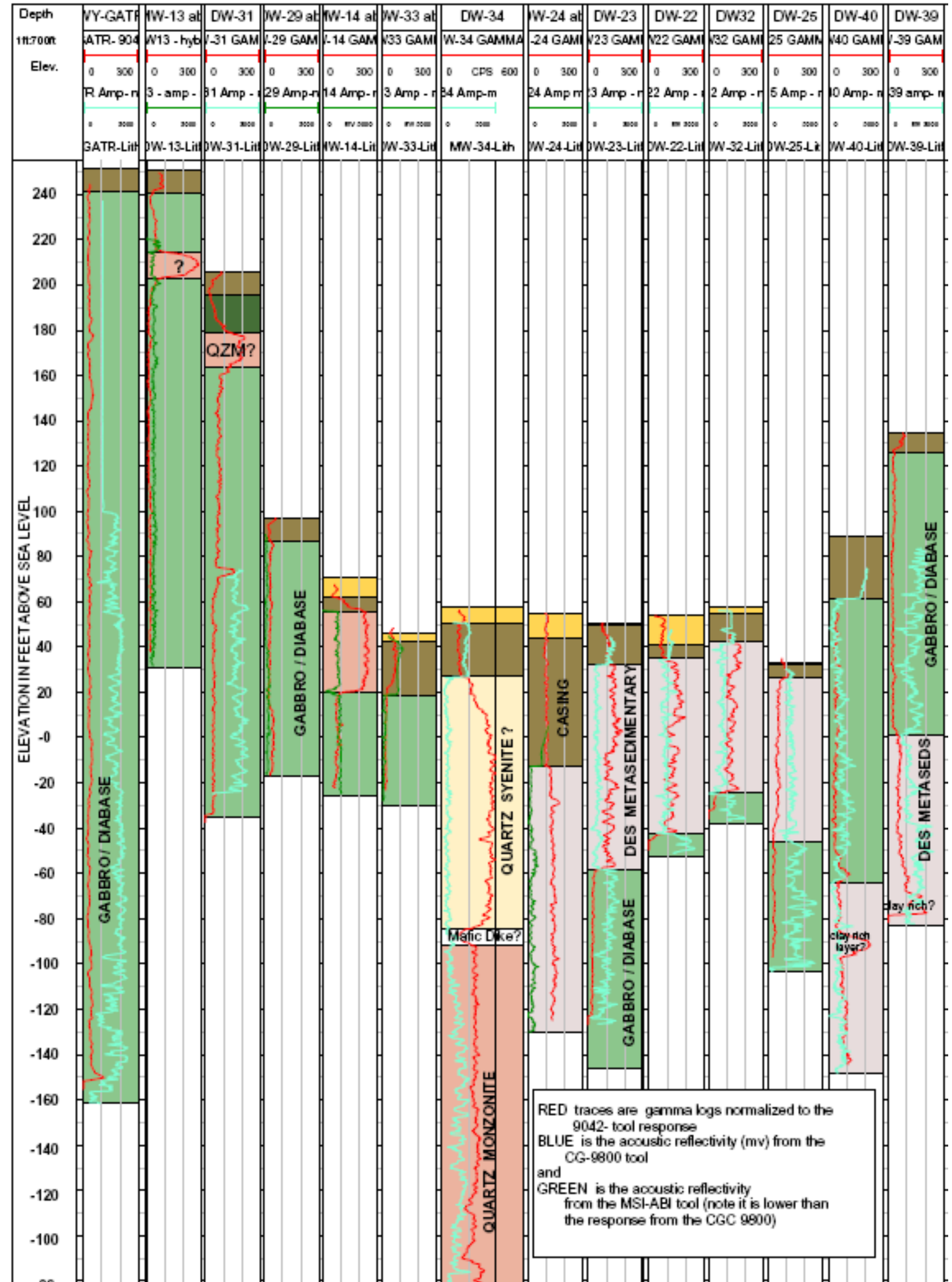
- Manual plot of acoustic reflectivity and gamma, which group according to rock type
- Core and drilling observation and **predictive use** of crossplot relations to determine rock type



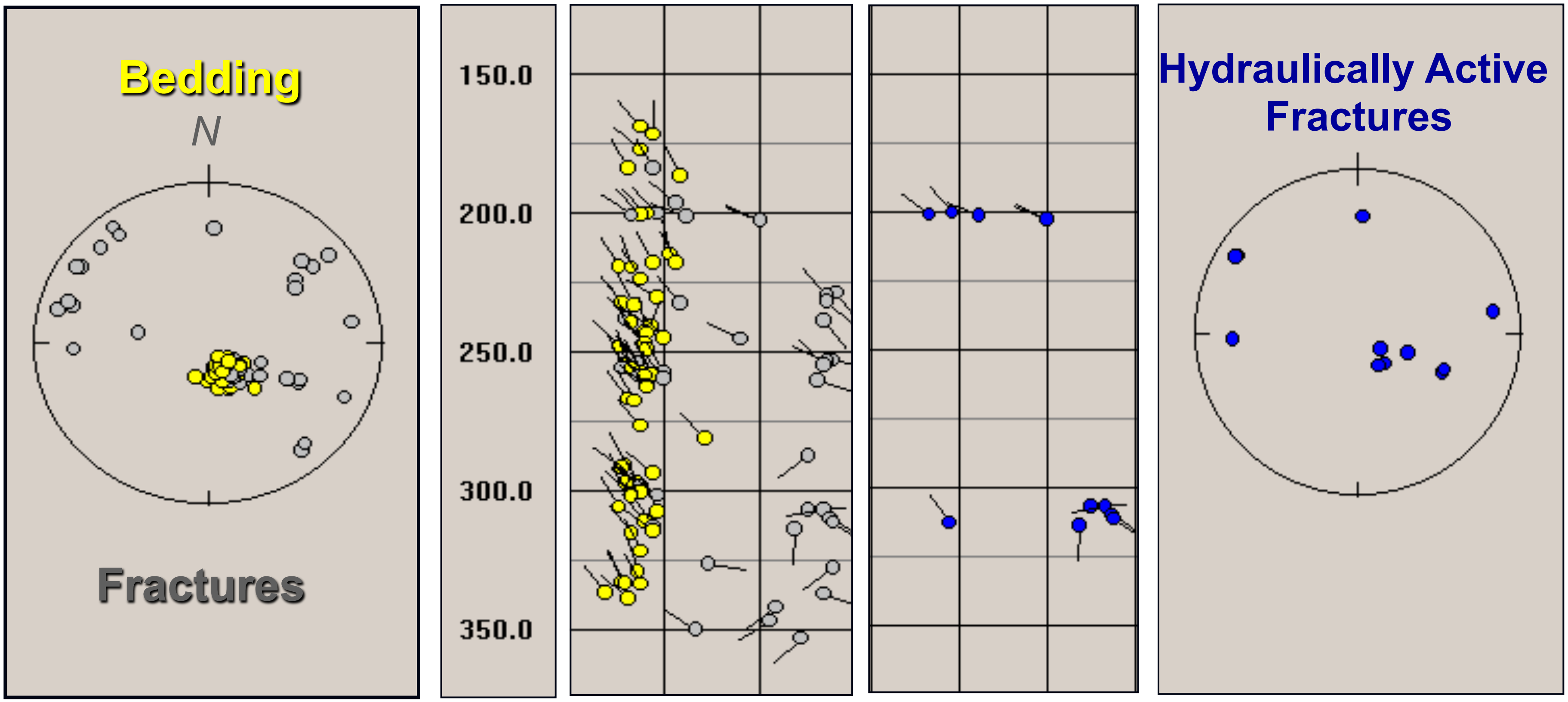
Putting it all together for site conceptual model

- Use crossplot relations to map the rock types (gabbro/diabase, metasediments, quartz monzonite, and rhyolite) across the site

- Here shown corrected to elevation at a site where they thought the contaminant distribution is related to lithology



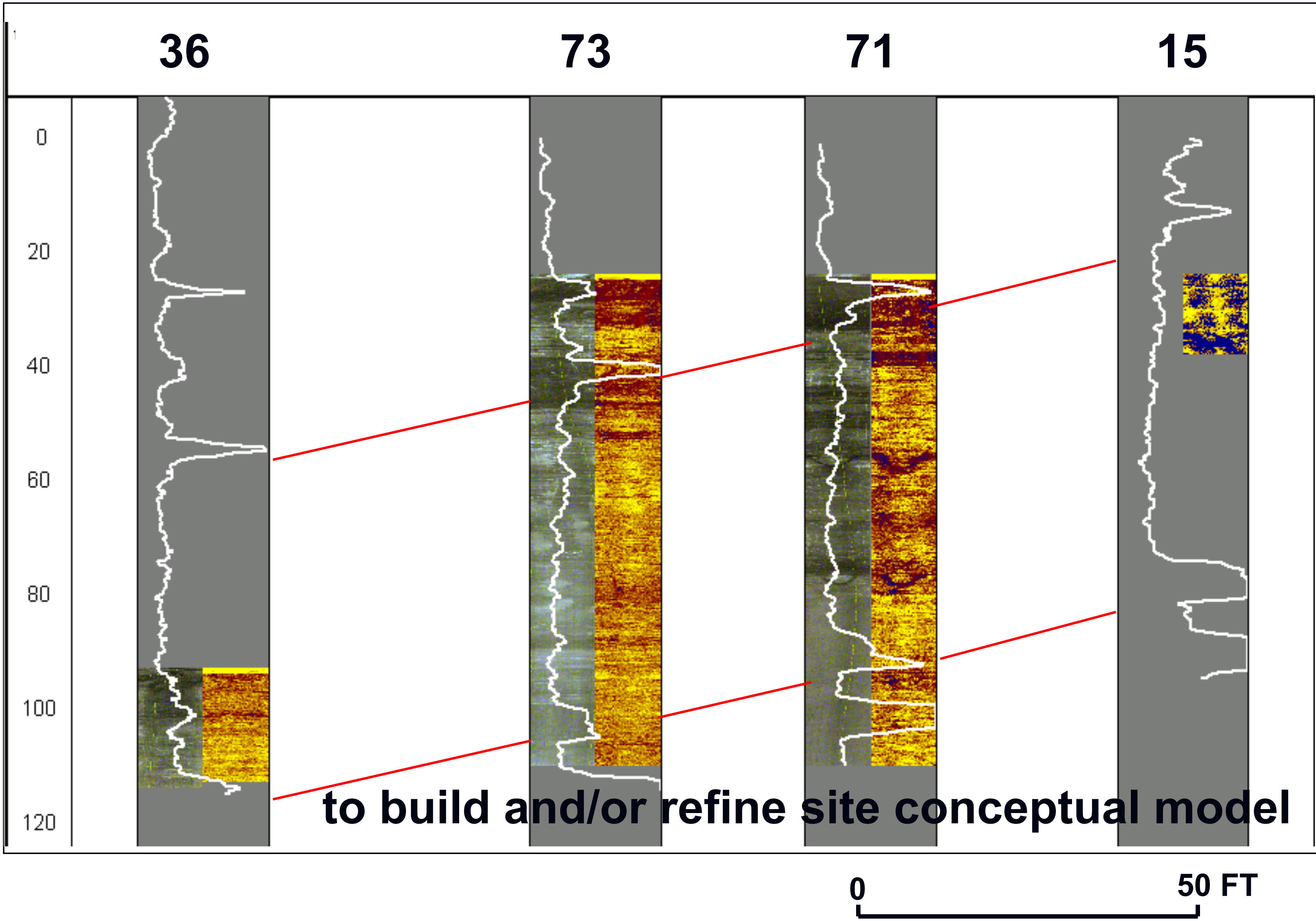
Bedding and Fractures in Sandstone



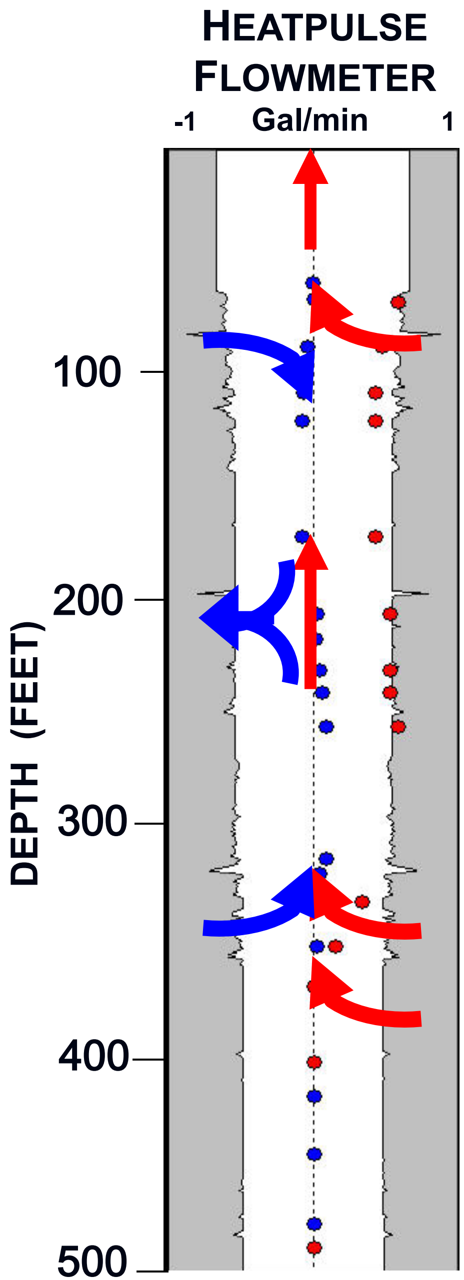
Combined interpretation - after hydraulic logging
identify patterns in fracturing and hydraulic properties

Ventura California USGS WRIR 00-4032

Gamma and Image Logs – Correlation across wells



4. Methods to characterize hydraulics

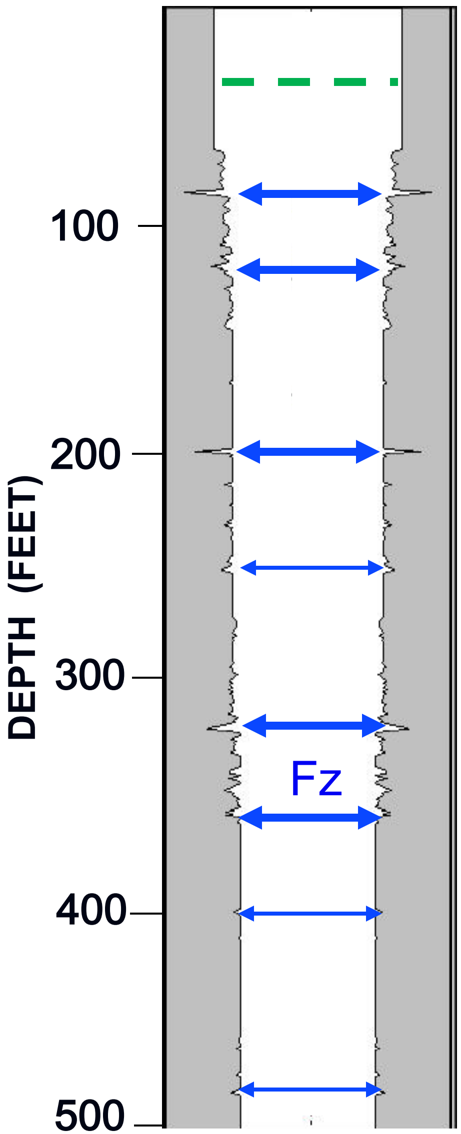


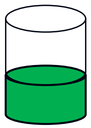
Vertical flow occurs if there are 2 or more transmissive zones with different heads (from high to low head)

FM (here shown as point measurements) can help identify which zones are "hydraulically active" under ambient conditions - here there is ambient flow

Under stressed conditions (pumping conditions) we two active fracture zones

Review of Concept:





Open hole sample and water level

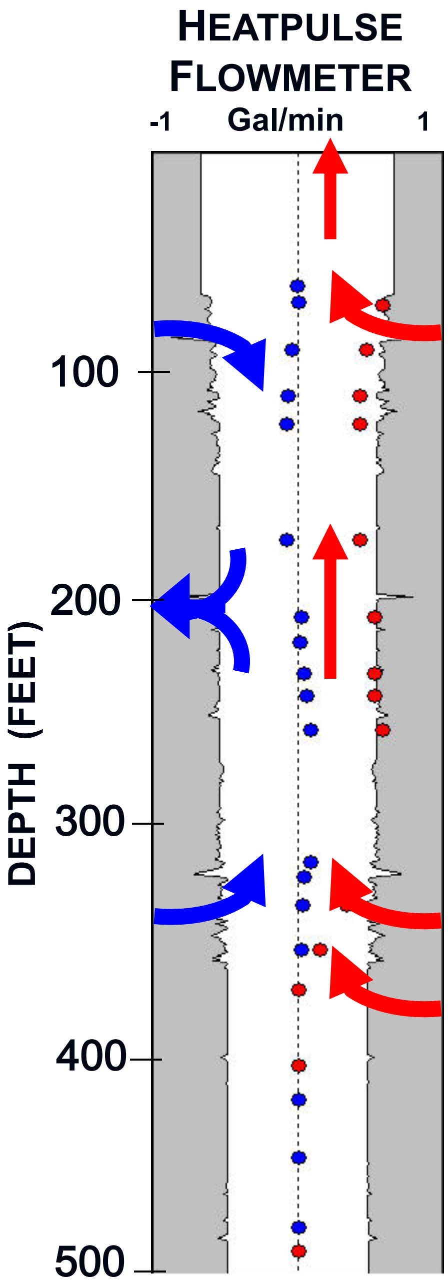
Several fractures/zones intersect a borehole

Each zone has a T and H.

Open-hole head and samples represent transmissivity weighted averages:

H = Σ (%T (H_{aq1}) + %T (H_{aq2}) +.. %T (H_{aqn}))

OHS = Σ (%T(C_{aq1}) + %T (C_{aq2}) +.. %T (C_{aqn}))



Flow Profiling

Series of vertical flow measurements made under ambient and stressed conditions

Qualitative:

- Identify ambient flow and potential for cross-contamination
- Identify transmissive fractures / zones

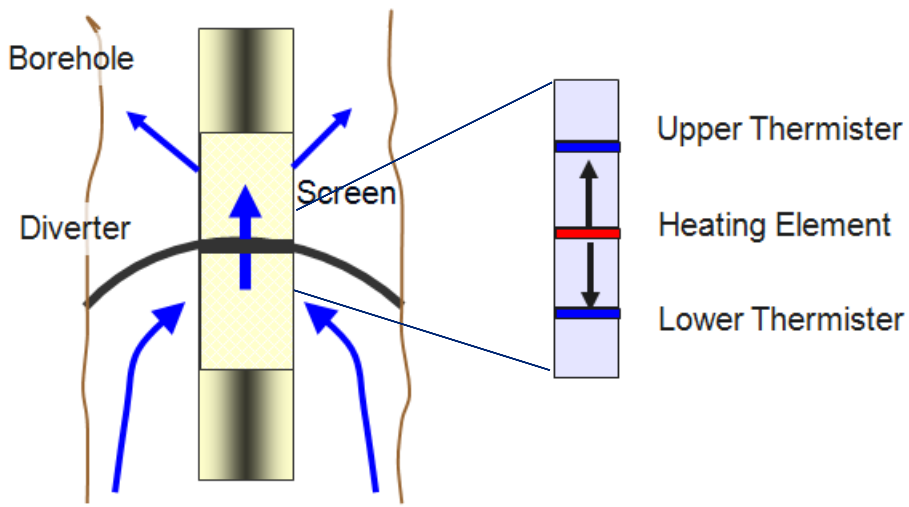
Quantitative:

- Need to account for changes in borehole storage
- Quantify transmissivity and head of discrete zones

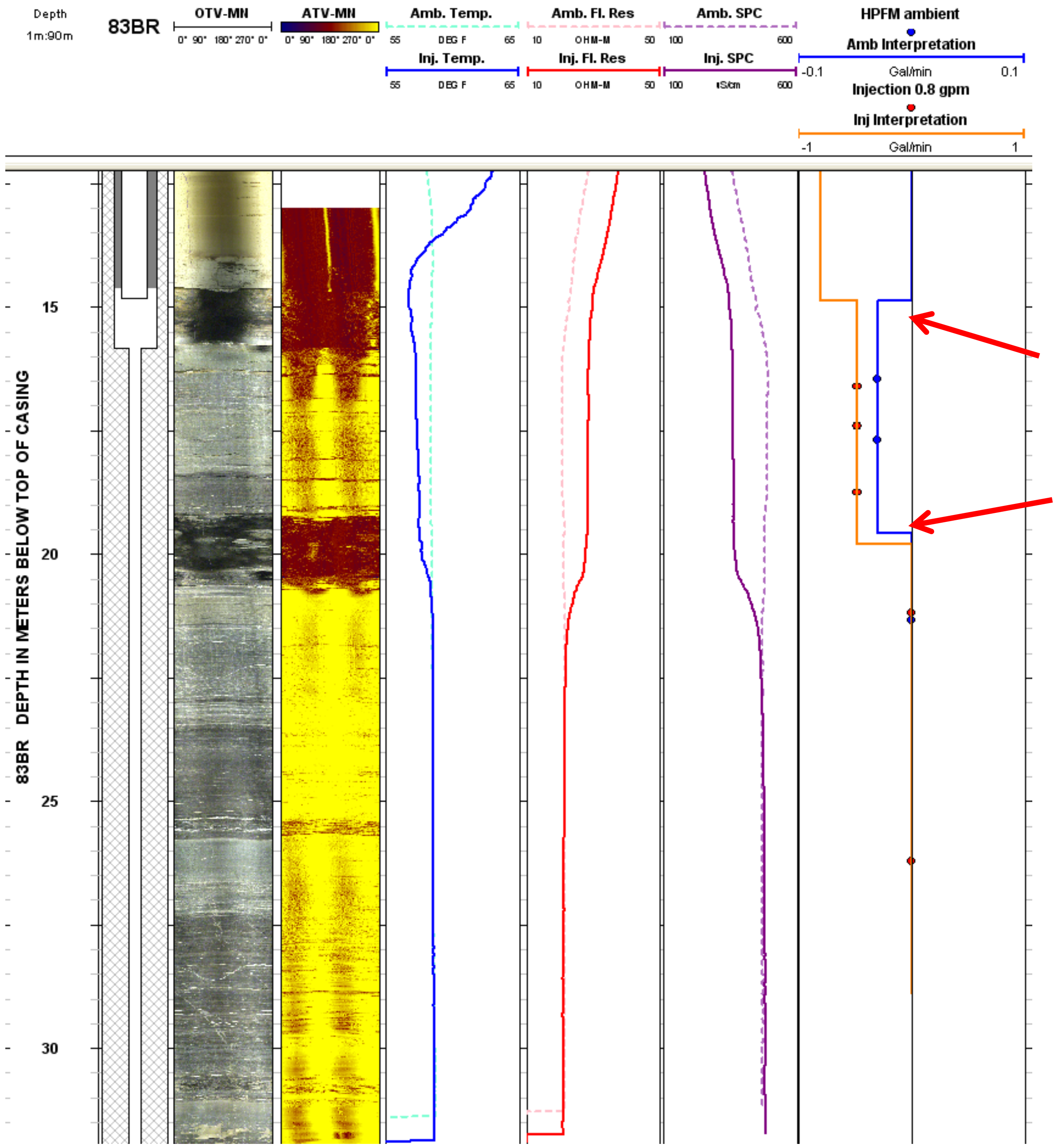
Heat-pulse flowmeter

Best practices

- Several measurements – with consistent shape and magnitude
- In casing and under known stressed flow
- Low-range confirmation



Fluid Data and flow



Heat-pulse flowmeter (HPFM) used to identify and quantify vertical flow rates under ambient and stressed (injection) conditions

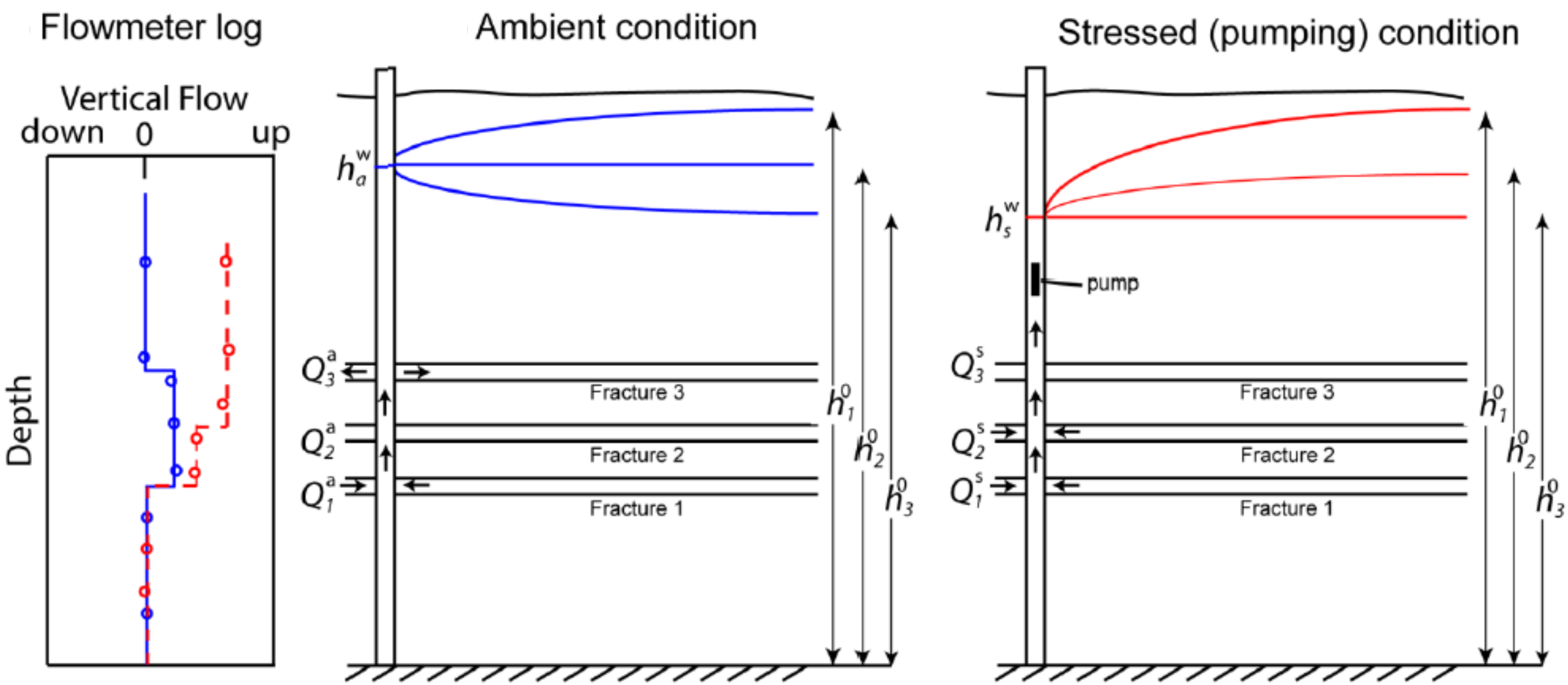
FLASH – used for modeling discrete zone head and transmissivity

- A new computer program in a simple-to-use format in Excel and Visual Basic for Applications (VBA)

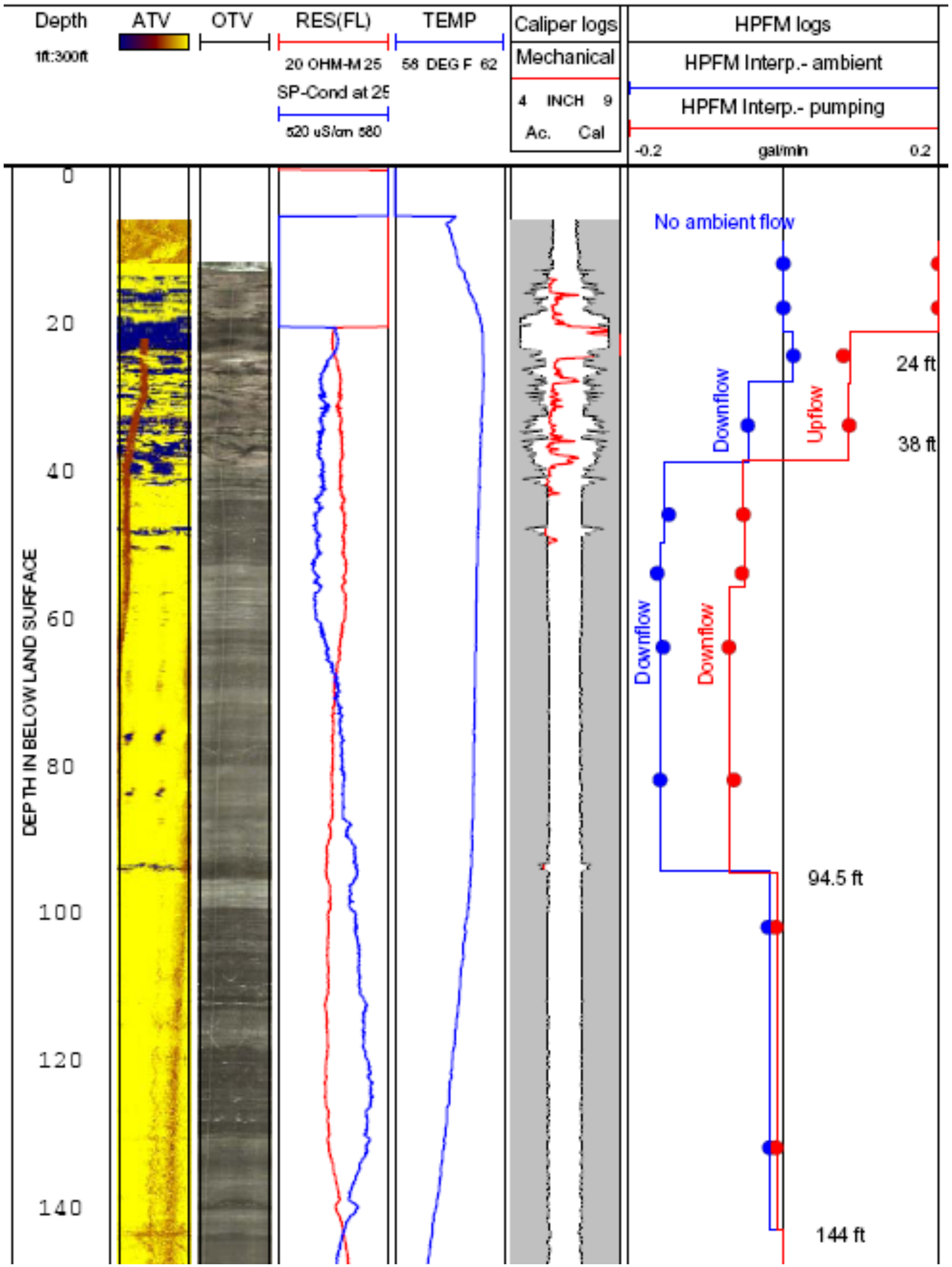
- Based on analytical solution for multi-layer, steady-state radial flow to a borehole.
  - Can represent the multi-layers as fractures or
  - as an aquifer layer

- Reference:
  Day-Lewis et al, 2011, A computer program for flow-log analysis of single holes (FLASH): Ground Water, doi:10.1111/j.1745-6584.2011.00798.a

Conceptual model: a set of flowmeter measurements with multiple hydraulically active zones intersecting a well.



Example: NAWC 68BR

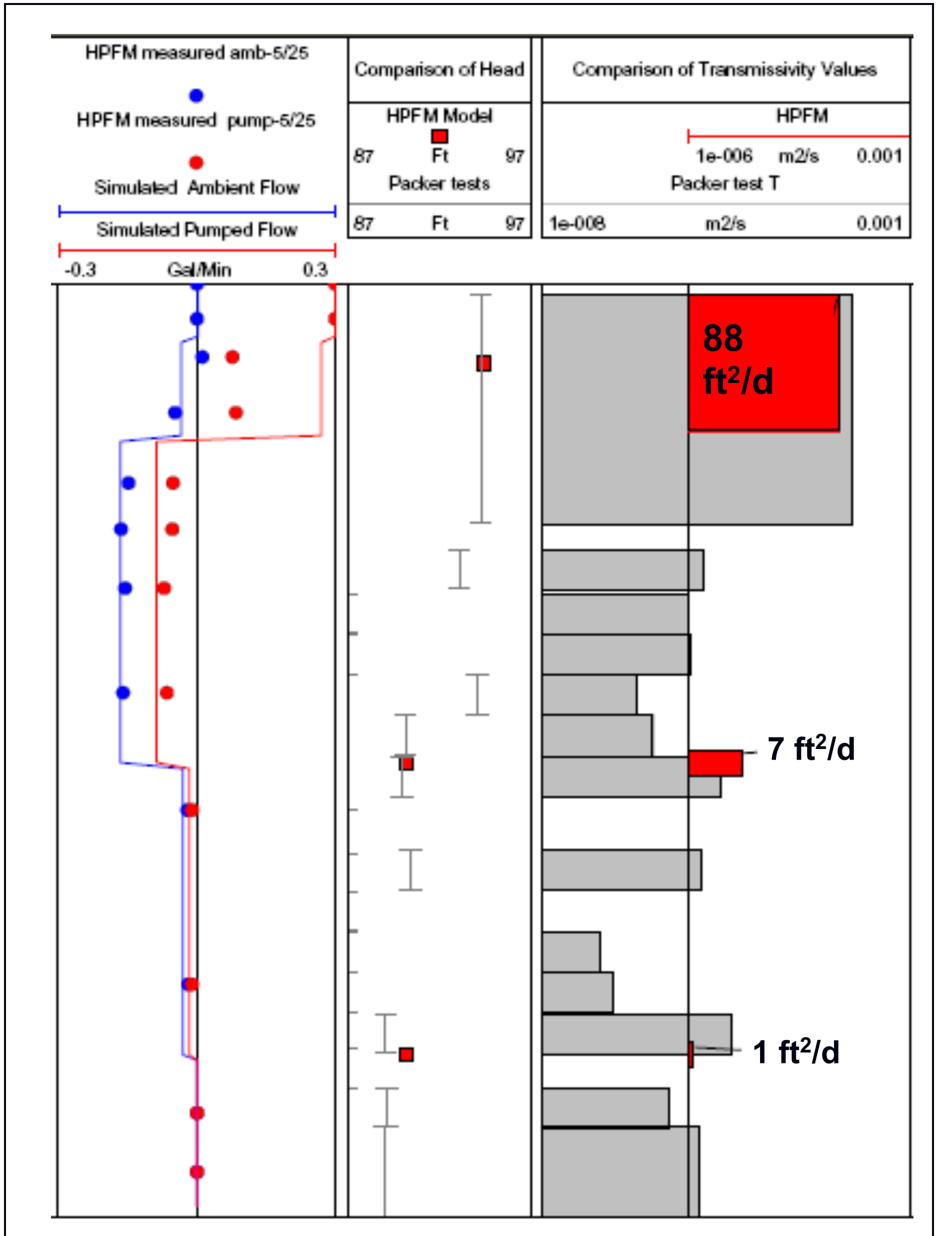


Ambient downflow 24 and 38 ft at - 0.16 gal/min

Exiting at 94.5 and 144 ft

Under Pumping water enters borehole at 24-38, 94.5 and 144 ft

Comparison of results to packer tests



Modeled heads and transmissivity:

flowmeter (red)

packer tests (gray)

Flowmeter:

- limited resolution
- dynamic range

New flow profiling tools might improve comparison. But we should always keep these limitations in mind.

FLASH Model – using 83BR

FLASH - Flow Log Analysis of Single Holes

USGS science for a changing world

REQUIRED INPUT:

Wellname: 83BR

Elevation of measuring point [FT]	100
Number of flow zones [-]	2
Well diameter [IN]	6
Drawdown [FT]	-0.20
Depth to ambient water level [FT]	9.37
Depth at bottom of casing [FT]	20
Depth at bottom of well [FT]	112
Radius of influence (R_0) [FT]	13.6
Total transmissivity (T_{total}) [FT²/day]	490.00

Run Solver

- Estimate Transmissivity
- Estimate ROI

- Solve without Regularization
- Solve with Regularization

ABS(Δh) maximum	2.00E+01
Regularization weight	1.00E-04
Tfactor minimum [-]	1.00E-04

Flow above layer bottom depths

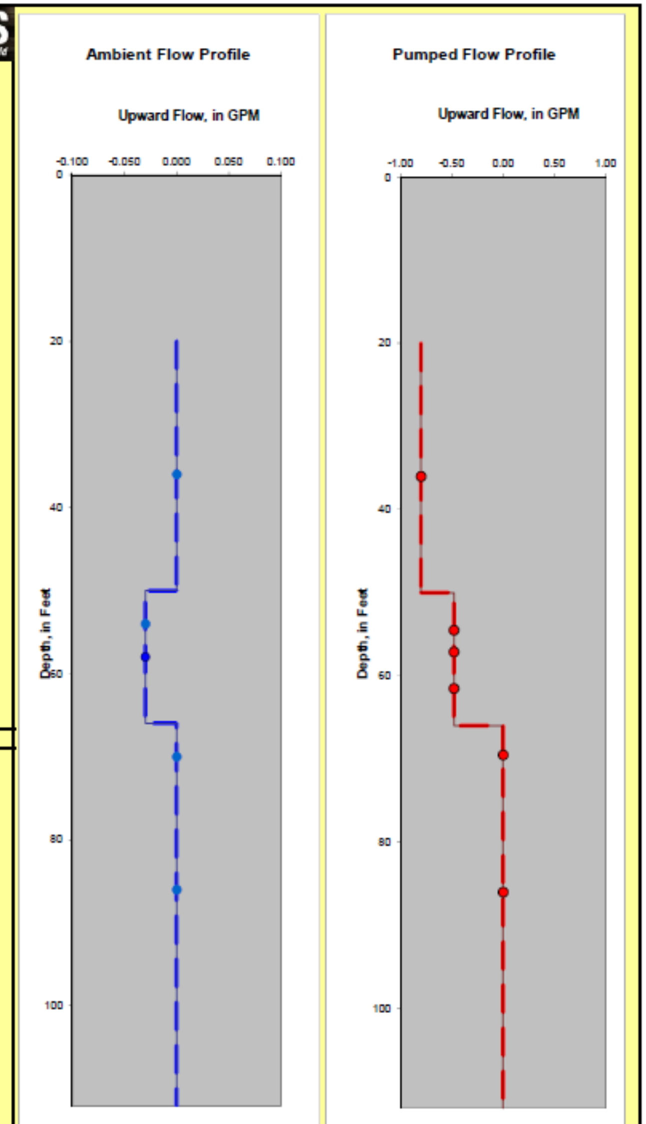
FRACTURES	Bottom Depth [FT]	Ambient [GPM]	Stressed [GPM]	Tfactor [FT²/D]	Δh [FT]	Farfield head [FT]
2	50.00	0.00	-0.80	0.44	0.02	90.65
1	66.00	-0.03	-0.48	0.56	-0.01	90.62

We enter flow profile, fracture depths, well info – and solve for zone T and head.

SIMULATED PROFILES (DO NOT EDIT)

MSE [GPM²]	1.04E-11	Sum T_{factor}	1.000	Sum Δh^2	0.00
Ambient WL [FT]	90.63	Estimated Ttotal [FT²/day]	490.000	Regularized Misfit	0.00
Pumped WL [FT]	90.83				

FRACTURES:	Depth [FT]	Ambient Flow above [GPM]	Stressed Flow above [GPM]	Ambient Error [GPM]	Stressed Error [GPM]	Zone T [FT²/day]	Fraction of total transmissivity
2	50.00	0.000	-0.800	0.000	0.000	214.371	0.437
1	66.00	-0.030	-0.480	0.000	0.000	275.629	0.563

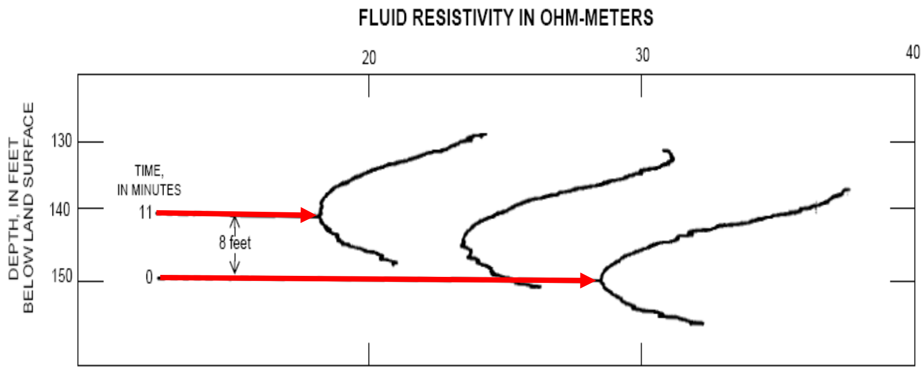


Dashed lines indicate interpretations of measured data. Solid lines indicate simulated profiles.

These results provided for comparison with logs presented in the previous talk

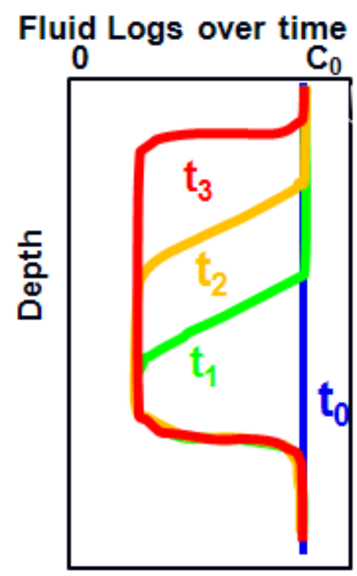
Flow-profiling methods – other than flowmeter methods

- Tracer-pulse methods
- Borehole-dilution logging



- Generally using salt or a color tracer added to the borehole in slug or complete fluid replacement monitored over time

- Extend the detection of flow rates



Summary

Borehole tools should be selected in order to answer particular questions or characterize your specific site.

Selected logs in the right combination can help the interpretation of the geology, structure, and fluids in the aquifer.

Data should be interpreted always thinking about whether this fits the site conceptual model – or helps reform the site conceptual model.

Flow profiling can provide direct measurement of hydraulic properties (T) and far-field head, providing insight into potential for cross contamination