Borehole Geophysical Logging for Groundwater Well Construction

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Geophysical Logging: Topics to Cover

- **What are borehole geophysical logs?** (history, background)
- **What purpose do they provide?** (why they are valuable, applications)
- **How do logging tools work?** (key technologies, measurement technique, what do the squiggly lines mean)
- **How do they help with groundwater well construction?** (geology/hydrology characterization, well design, well completion integrity)
- **Examples** (interpretation, highlight value and limitations)
- **Key Takeaways**

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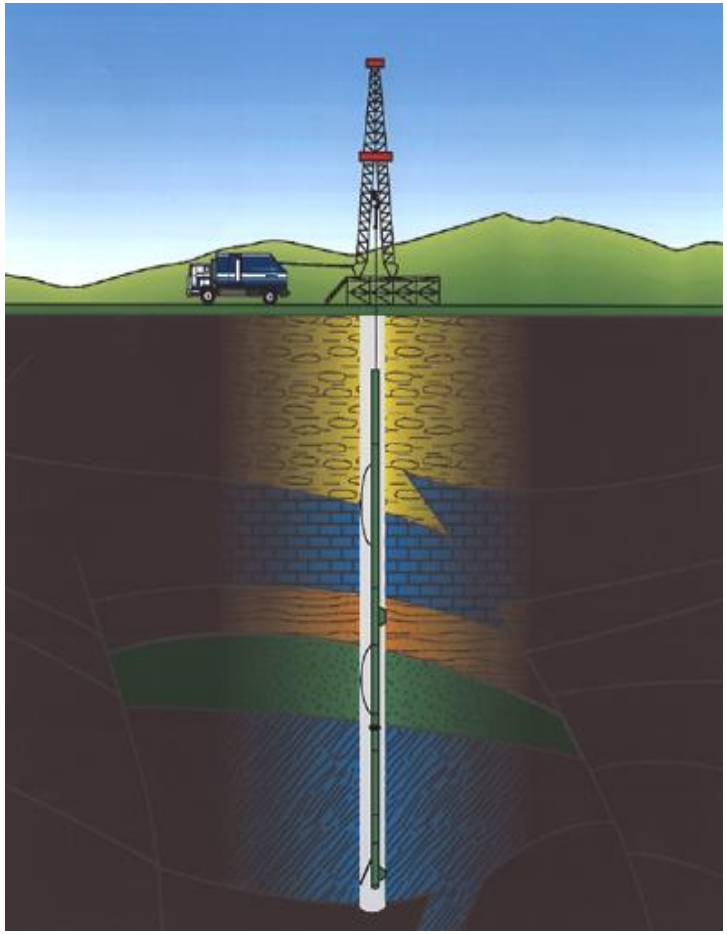
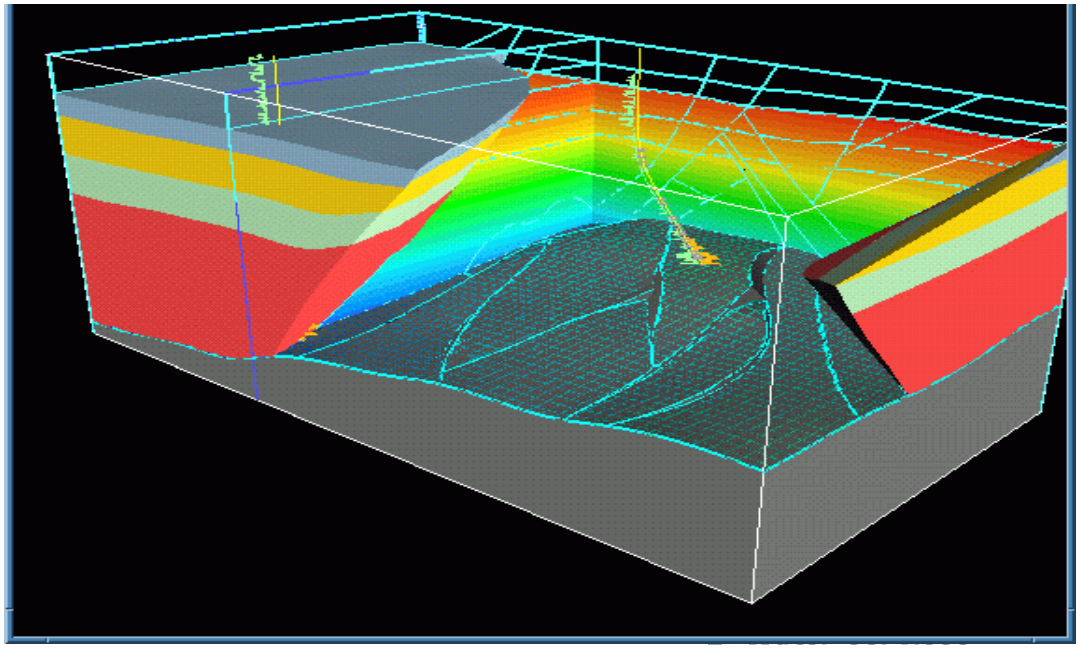
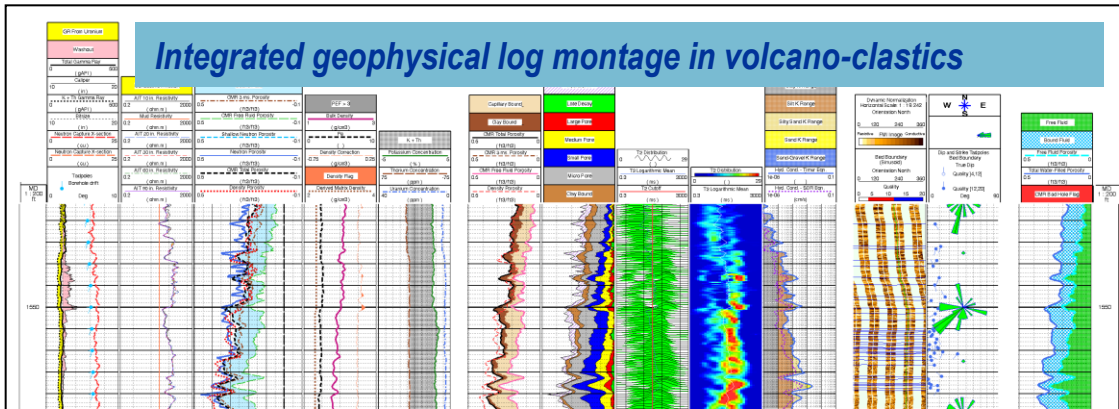
Geophysical Log Data:
In-situ 1-D Line Data (recorded nearly continuously in depth)





Borehole Geophysical Logging (also called Wireline Logging)

- Evaluates stratigraphy, numerous physical and chemical parameters
- In-situ measurement (non-invasive, but can take core/water samples)
- Nearly continuous vertical coverage (6 in. or less sampling interval)
- High vertical resolution (typically about 1-ft, as good as < 1 in.)
- Shallow depth of investigation (typically less than 1-ft, max. ~7-ft)
- Wide range of technologies and measurement types (>50 types)
- Mature, proven technology – well calibrated measurement (if logging tool is well characterized!)

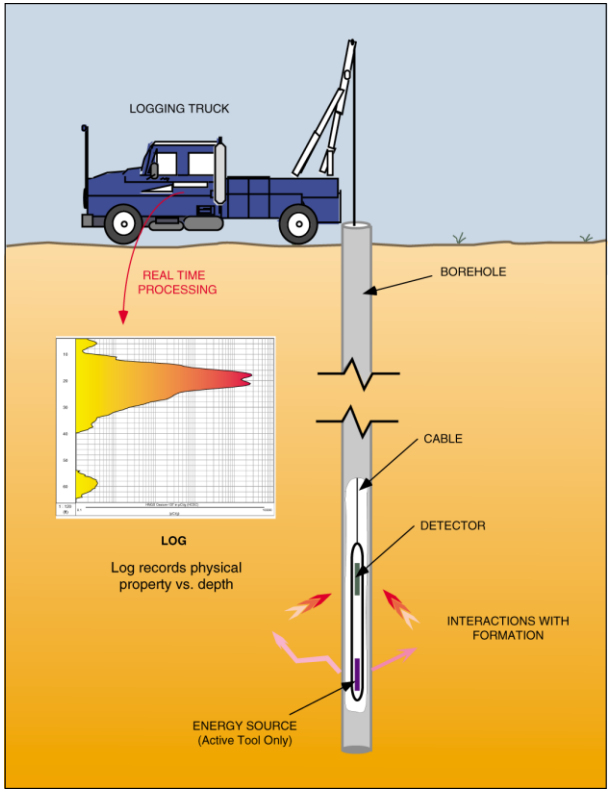


History of Borehole Geophysical Logging

- First log run by Schlumberger brothers in France in 1927
  - Application of surface resistivity in wellbore
- Numerous tools and acquisition systems added over the years
  - Especially with computer and microprocessor revolution
- Mature industry
  - One of principal means for wellbore characterization across most subsurface evaluation applications/disciplines, but wide range of sophistication (industry dependent)

What do geophysical logs measure? ENERGY

- Electromagnetic energy
  - Passive electrical (SP)
  - Active electrical, low frequency electromagnetic (bulk DC & induction resistivity, resistivity imaging)
  - Active high frequency microwave electromagnetic (bulk dielectric properties)
  - Active NMR nuclear magnetic resonance
- Acoustic energy
  - Active “low” frequency compressional (P) wave, shear (S) wave, Stoneley (tube) wave (monopole & dipole sonic)
  - Active high frequency compressional (ultrasonic/acoustic televiewer)
  - Passive P and S wave (micro-seismic monitoring)



- Nuclear energy
  - Passive natural gamma ray (gross, spectral – K, U, Th)
  - Active neutron-neutron (neutron porosity)
  - Active gamma-gamma (density, photoelectric factor)
  - Active neutron-gamma (neutron capture cross-section, elemental spectroscopy)
- Potential & Kinetic energy
  - In-situ formation pressure and pore fluid sampling (active and passive)
  - In well flow (active and passive)
  - Temperature and strain
- Mechanical energy
  - Caliper
  - Sidewall coring

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Types of Downhole Technologies

Conventional open-hole logging
Resistivity, SP, gamma ray, acoustic, porosity, density

Advanced open-hole logging
Magnetic resonance, oriented borehole wall imaging, geochemical spectroscopy, dipole sonic

Cased-hole logging
Cement bond, casing corrosion, gravel pack log, formation evaluation (fewer options than open hole)

Profiling (cross-well, well-to-surface)
VSP, acoustic reflection/tomography, resistivity tomo.

Sampling and testing
Wireline packer testing, wireline sidewall coring

Fluid logs
Temperature, spinner flow, hydrophysical, borescope, heat-pulse flow, dye tracer

Logging while drilling (LWD)

Measurements while drilling (MWD)

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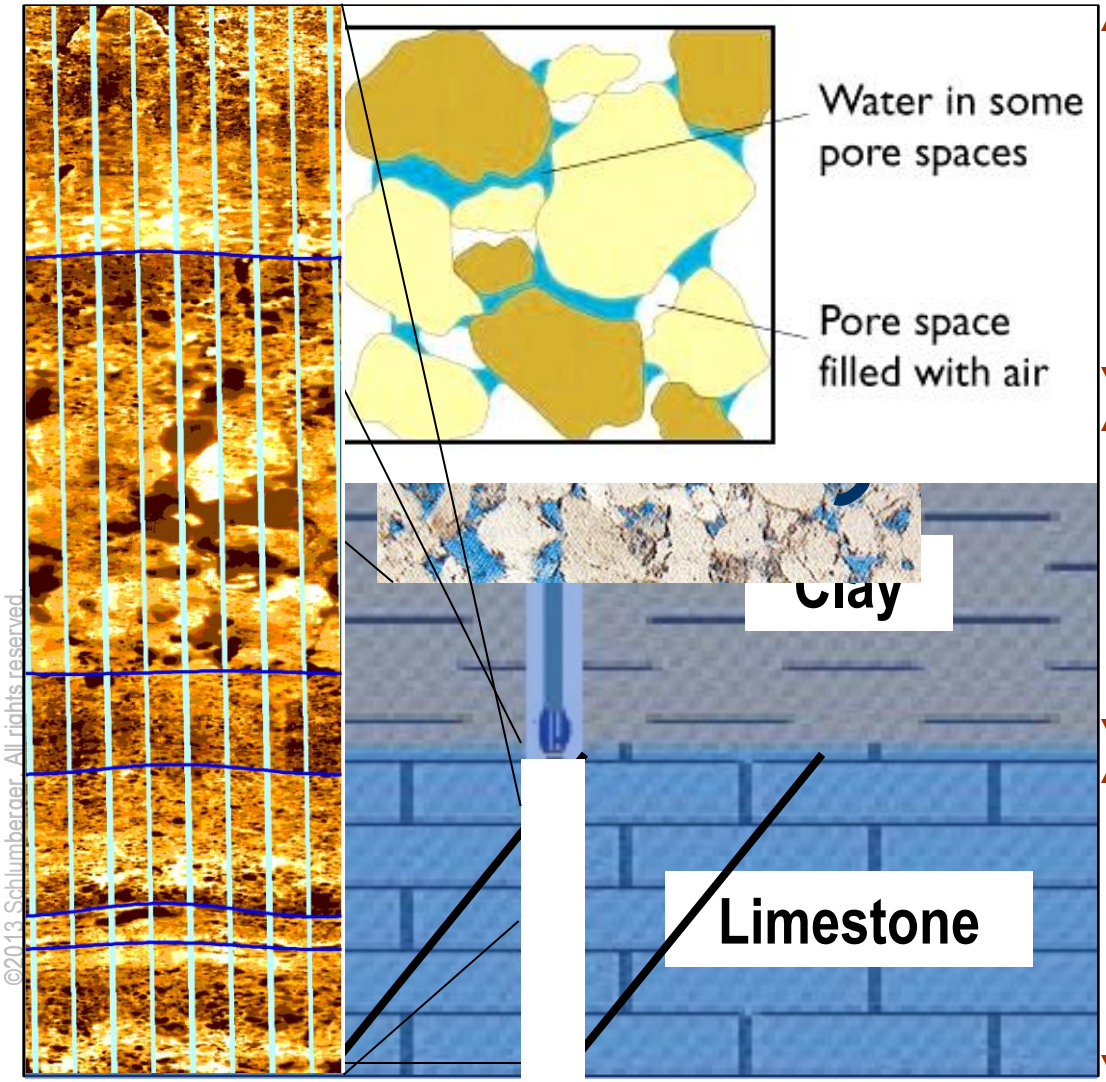
Geophysical Logs Can Provide:



Geology and Lithology

Bed thickness, continuity, dip

Lithology & mineralogy

Aquifer Properties

Water table, pore pressure (head)

Total and effective porosity

Hydraulic conductivity, dispersivity

Aquifer Compressibility

Storativity, specific yield

Moisture content & capillary pressure

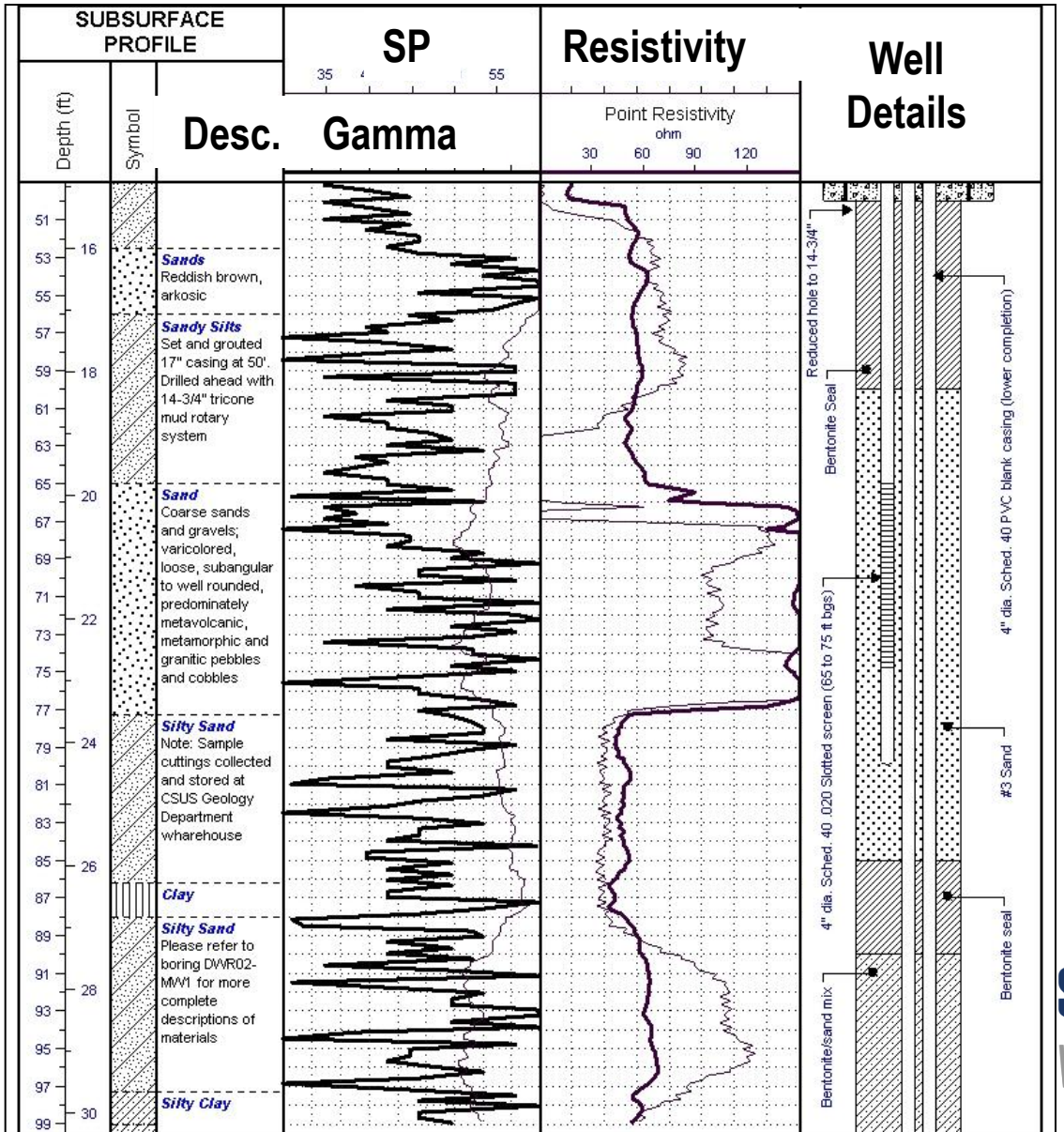
Fluid Properties

Water quality, temperature, pH

Carbonate Characteristics

Karst development, micro vs. meso vs. macro porosity, fracturing

Conventional Elogs



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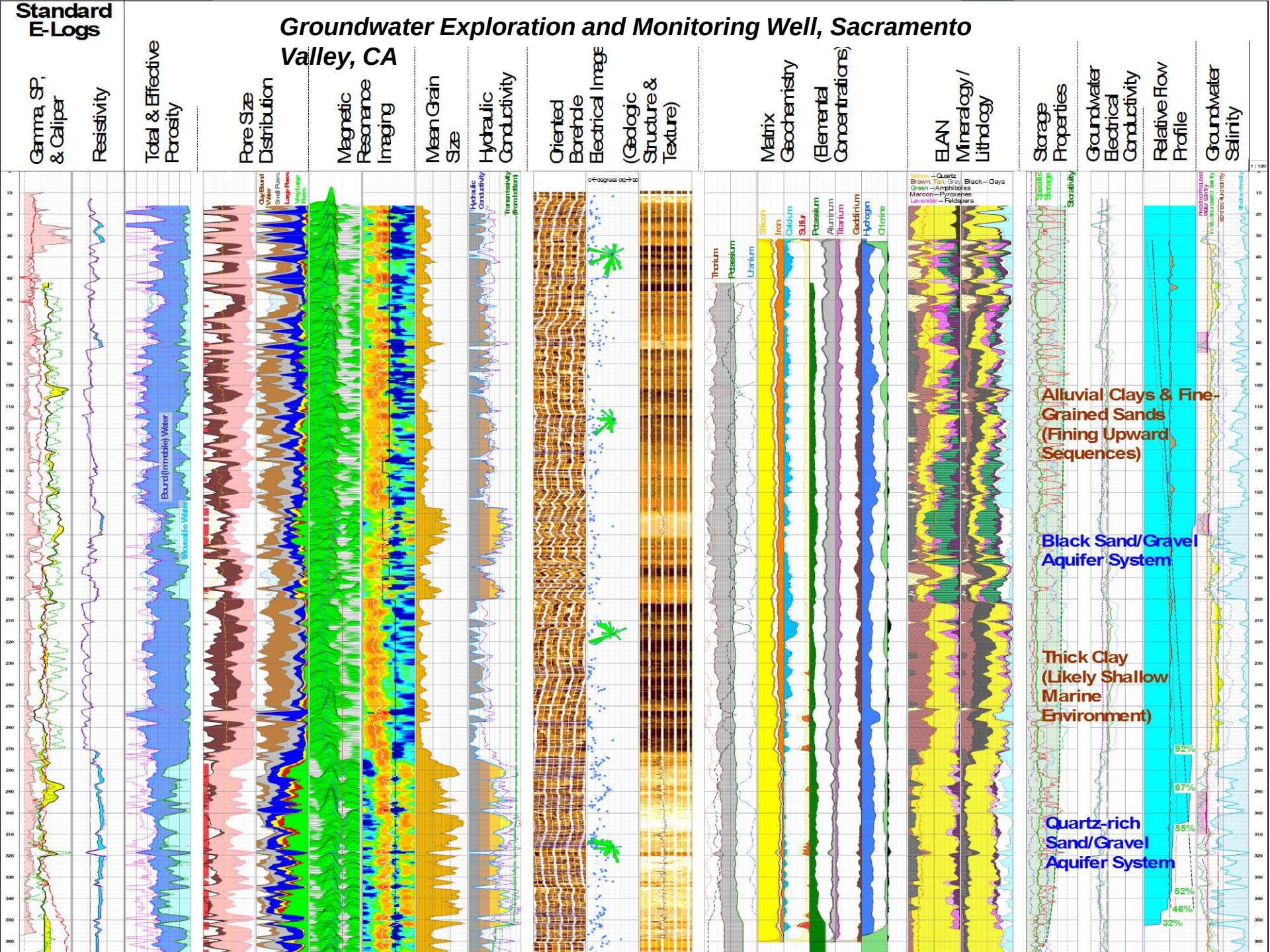
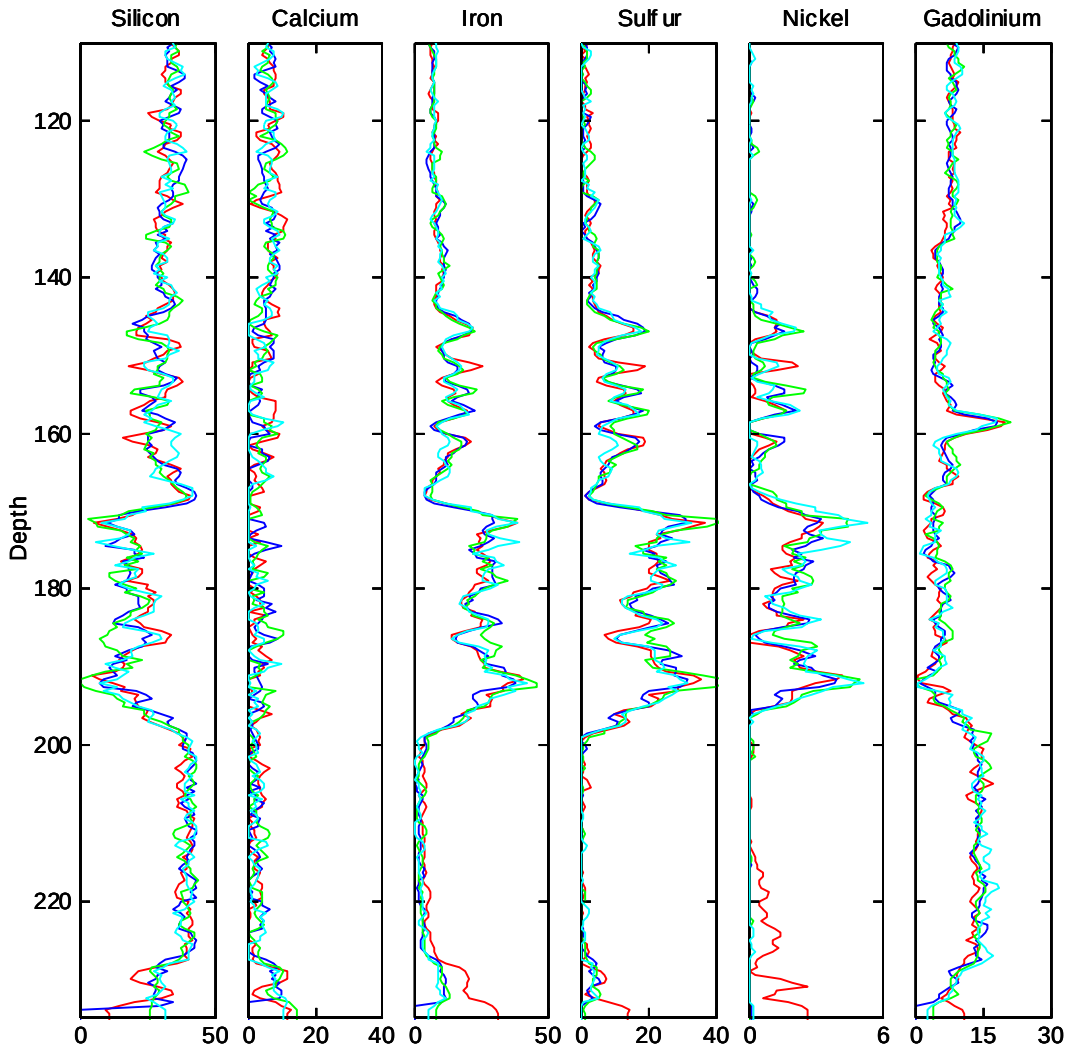

Standard E-Logs
Groundwater Exploration and Monitoring Well, Sacramento Valley, CA
Gamma, SP, & Caliper
Resistivity
Total & Effective Porosity
Pore Size Distribution
Magnetic Resonance Imaging
Mean Grain Size
Hydraulic Conductivity
Oriented Borehole Electrical Image
(Geologic Structure & Texture)
Matrix Geochemistry
(Elemental Concentrations)
ELAN Mineralogy / Lithology
Storage Properties
Groundwater Electrical Conductivity
Relative Flow Profile
Groundwater Salinity
Alluvial Clays & Fine-Grained Sands (Fining Upward Sequences)
Black Sand/Gravel Aquifer System
Thick Clay (Likely Shallow Marine Environment)
Quartz-rich Sand/Gravel Aquifer System
92%
87%
55%
52%
46%
32%

Logging Goal: Precise, Accurate Data

Consistent results (hole to hole, tool to tool)

Precise:
4 x passes



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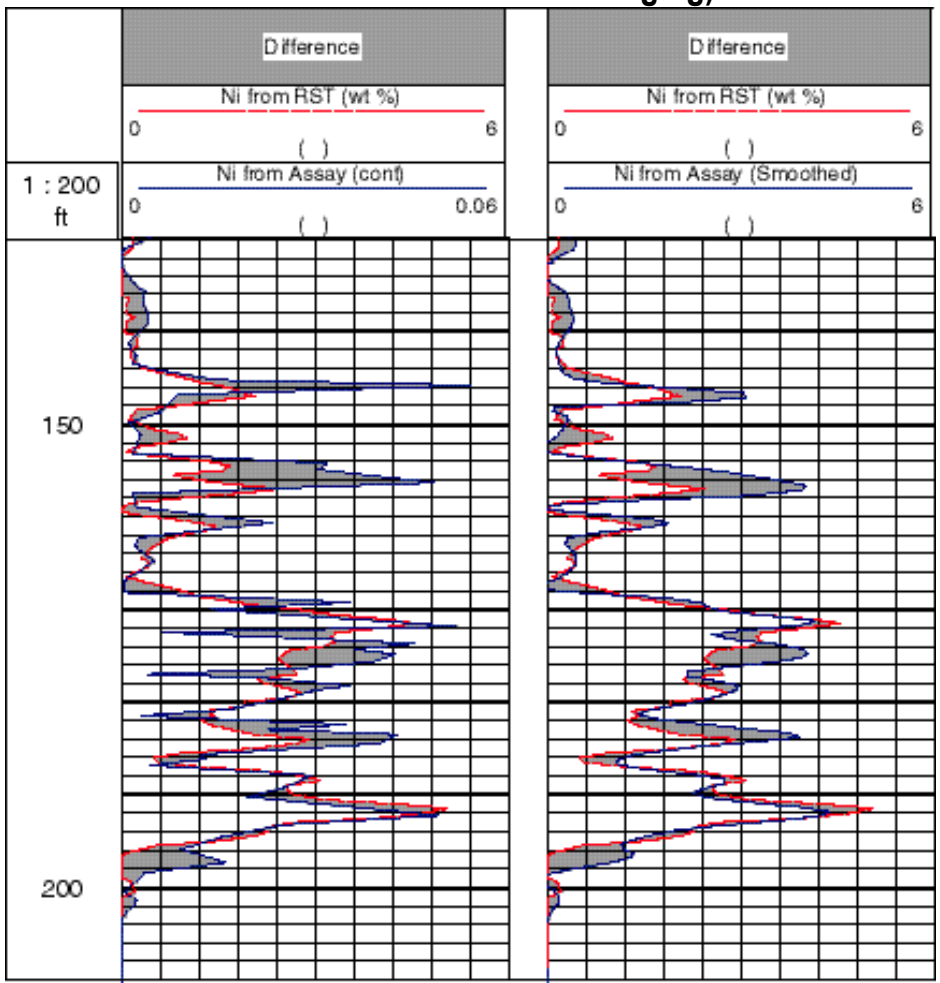
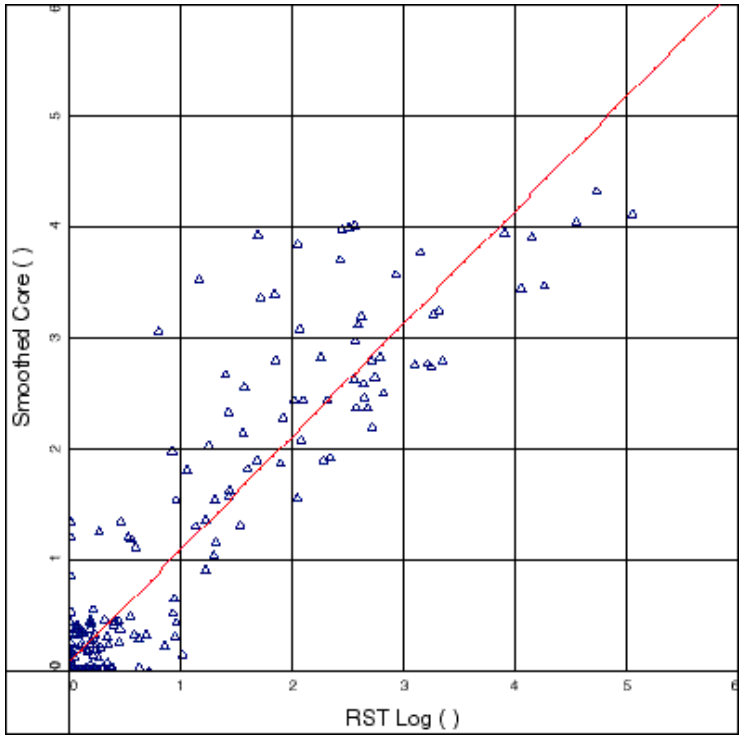
Accurate: Log Comparison to Core Lab Analysis

Unfiltered Core Results

Filtered Core Results (to match log vertical averaging)



Log vs. Filtered Core Assay Crossplot
R^2 = 0.85



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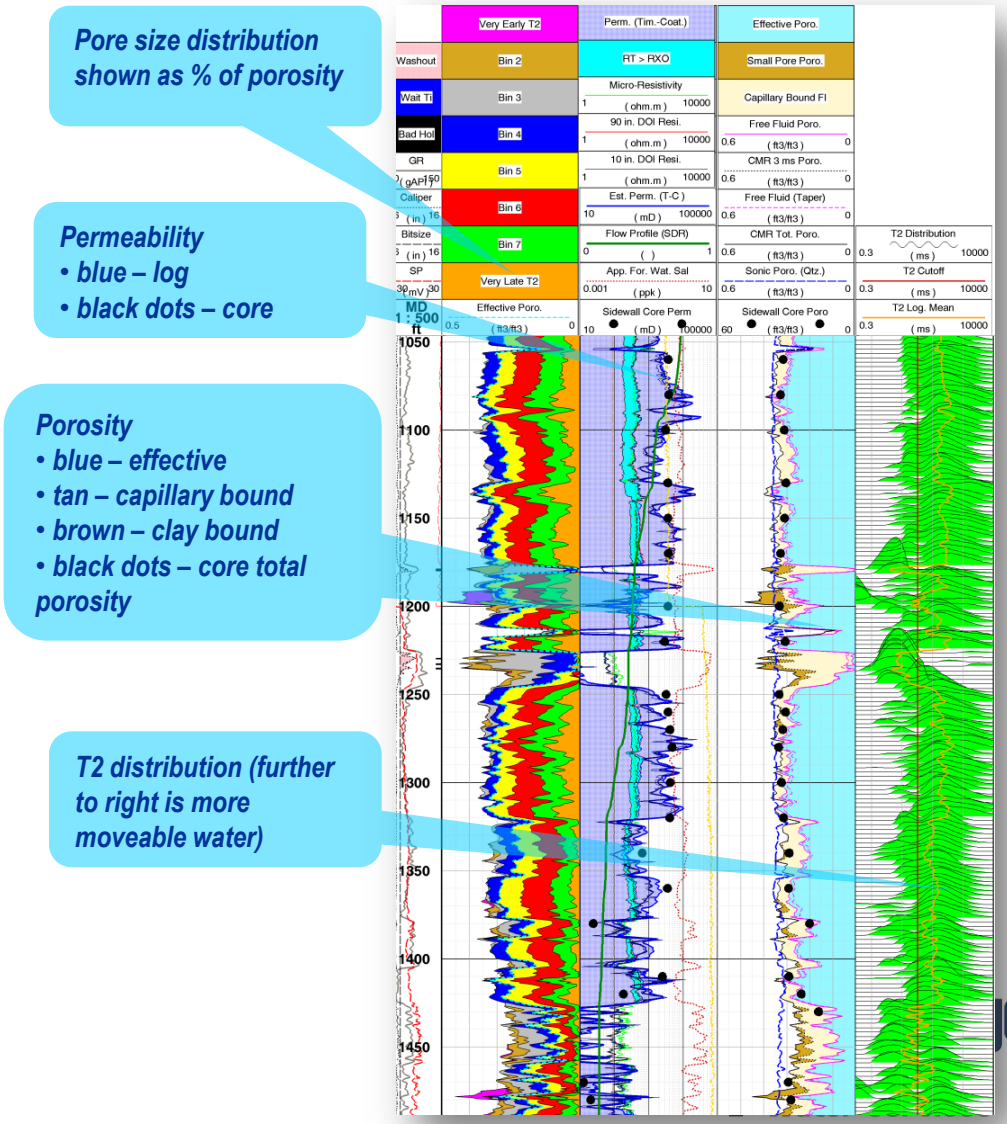
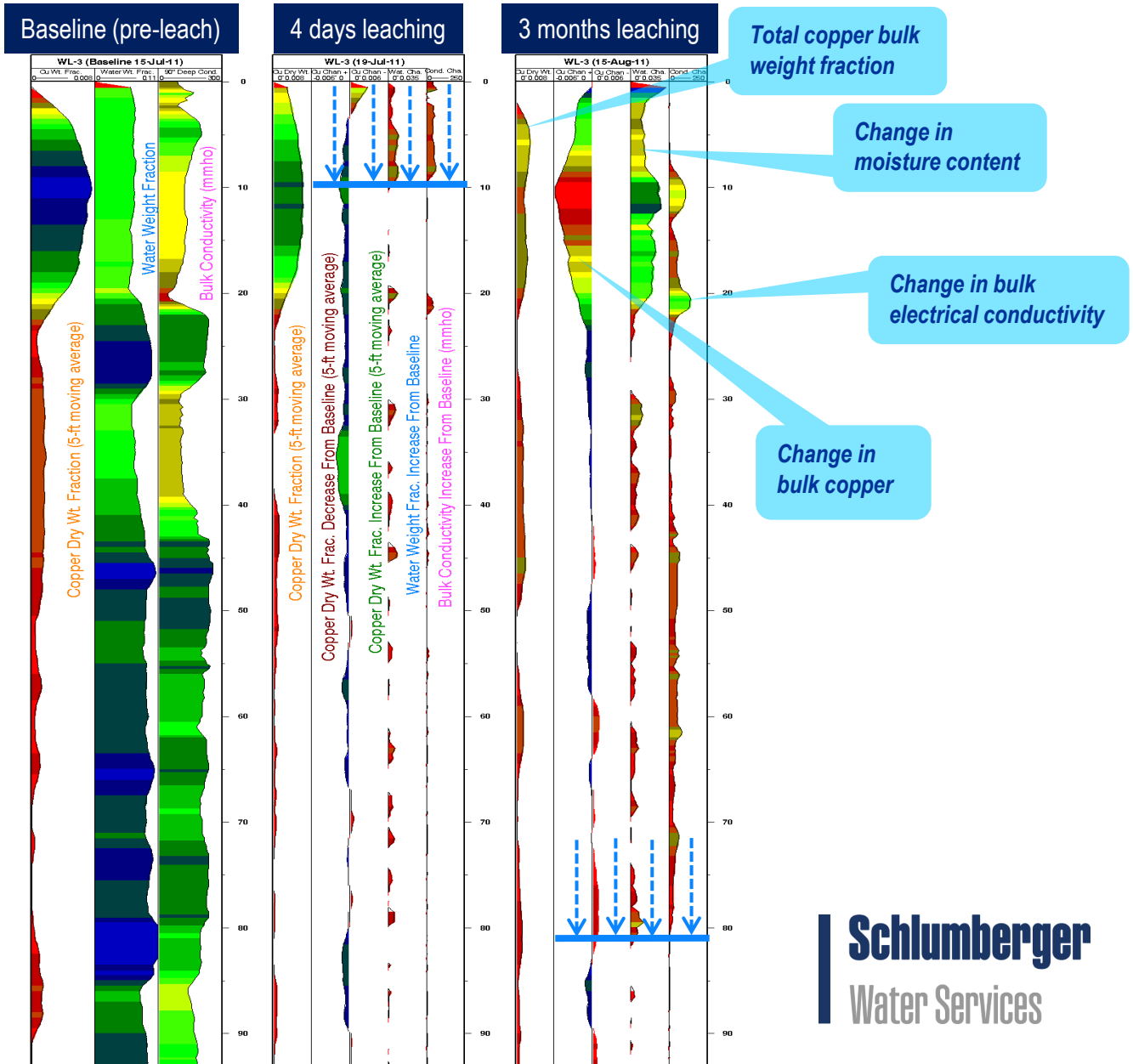
Magnetic Resonance Geophysical Log Results vs. Core

- Central Texas water resource development project
- Measured properties
  - Total and effective porosity
  - Pore size distribution
  - Estimated permeability/ hydraulic conductivity
- Good agreement between log and core results for porosity and permeability
- Clearly delineates most productive zones; used directly for production well design



Wireline Log Pre/Post Leach Analysis In Copper Heap



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Log Data Quality:
Technology Calibration and Characterization

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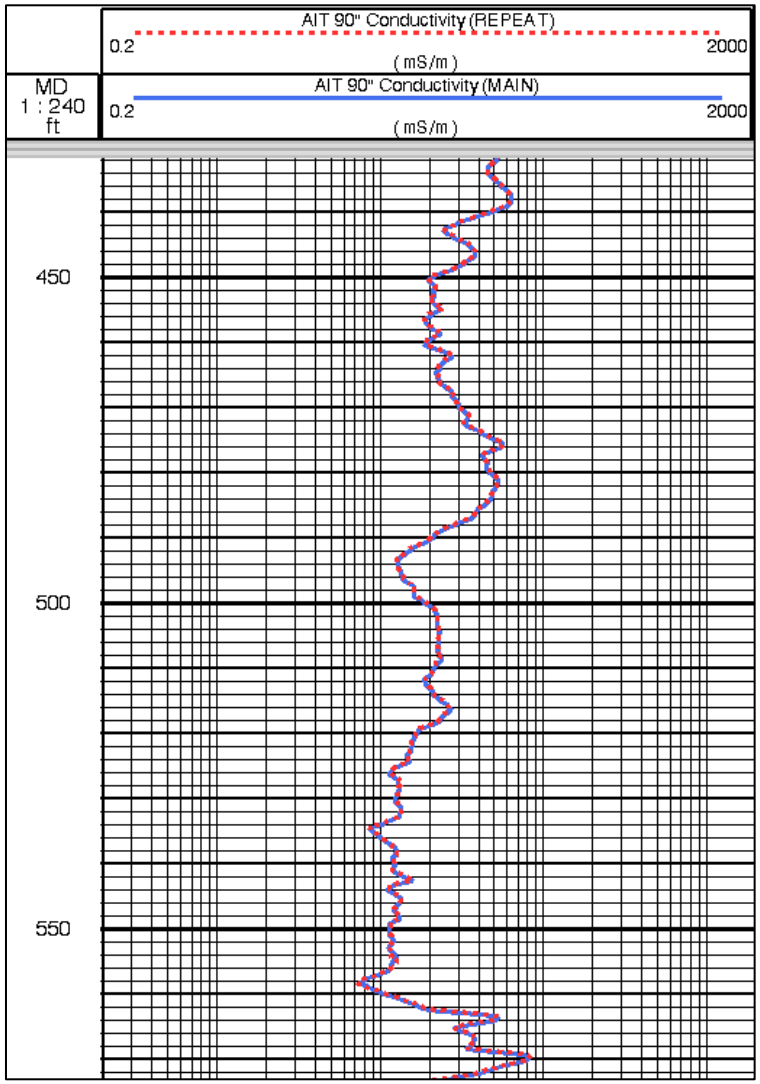
Log Data Quality: Reliable Acquisition

- Rigorous depth control (redundant systems)
- Repeatable
- Properly calibrated in field
- Pre- and post-logging validation
- Real-time log QA/QC



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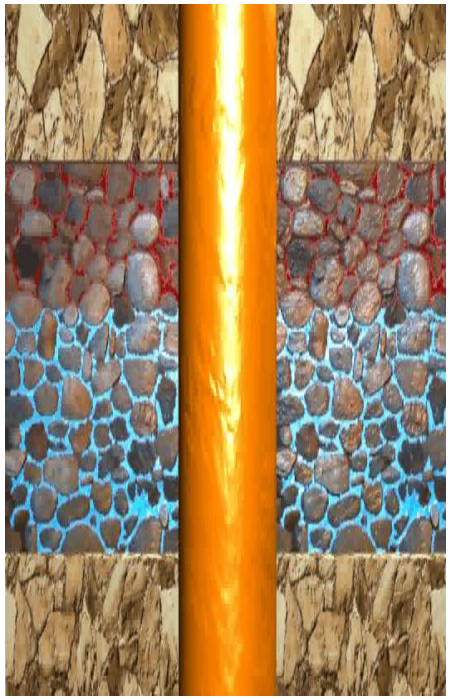
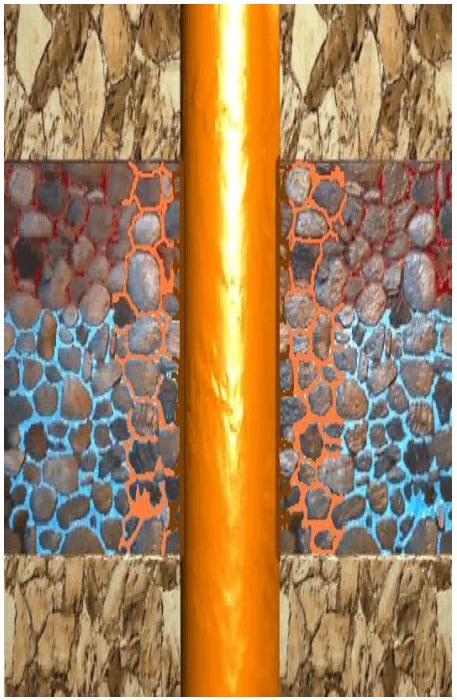
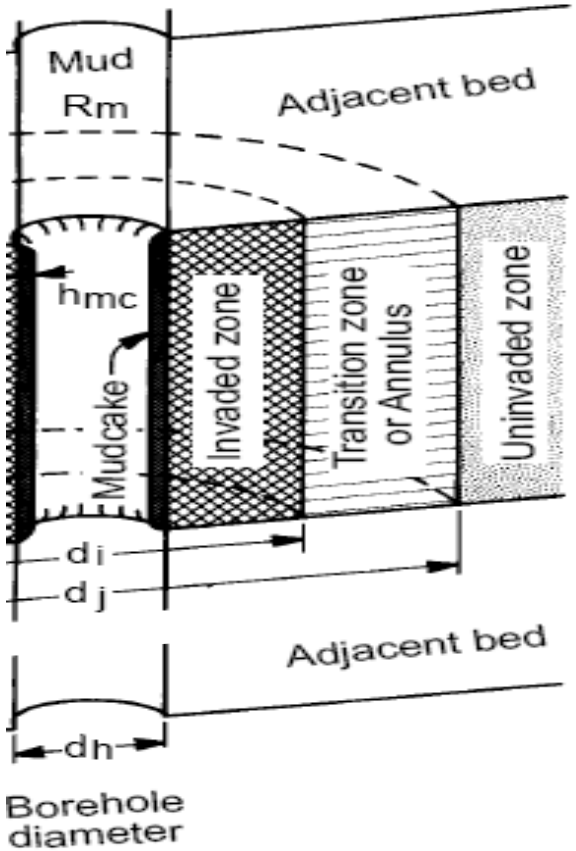
Log Data Quality: Borehole Fluid Invasion







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Log Quality: Processing and Interpretation

- Apply environmental corrections
- Petrophysical processing to derive/estimate subsurface properties of interest from processed measured parameters
- Advanced interpretation
- Upscaling

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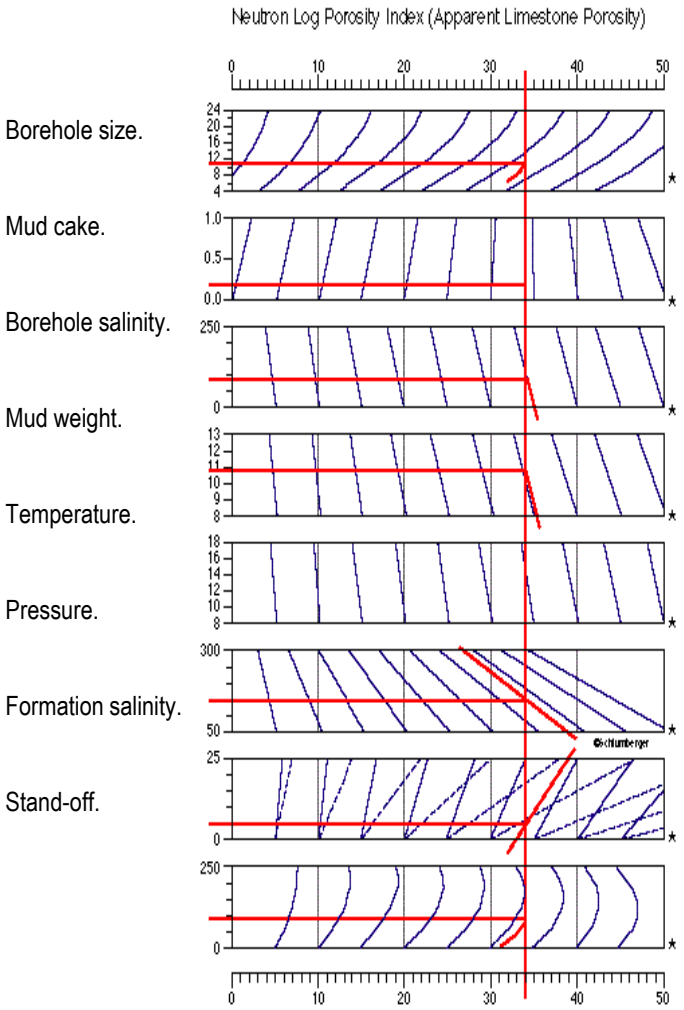
Neutron Porosity Environmental Corrections

- Neutron measurements have numerous environmental issues that need corrections applied
- In addition, the measurement is sensitive to lithology and usually there are separate outputs for limestone, sandstone, and dolomite porosity
- Final corrected log corresponds to hydrogen index (HI) for a particular lithology
- HI is sensitive not only to water, but also bound in certain minerals such as clay and gypsum that contain large amounts of hydrogen)



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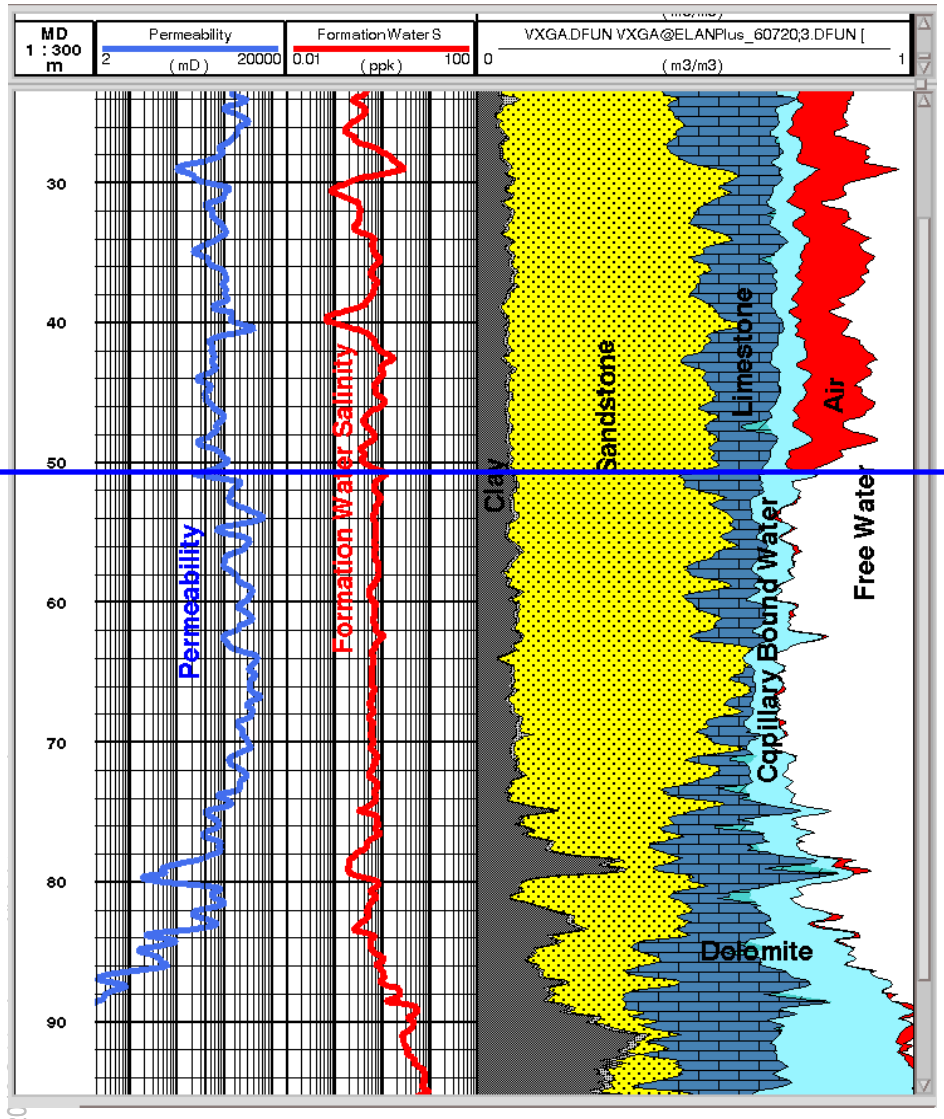
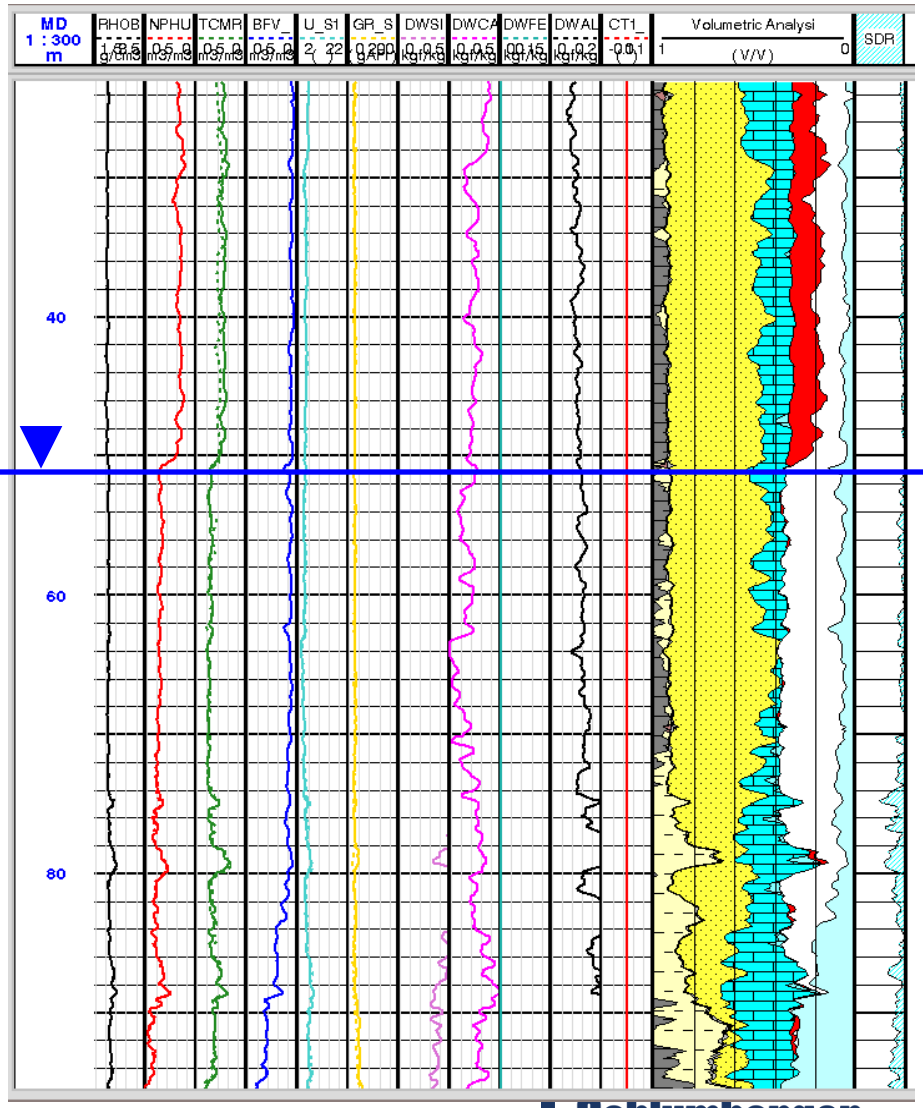
Integrated Log Analysis (Unconfined Desert Aquifer)





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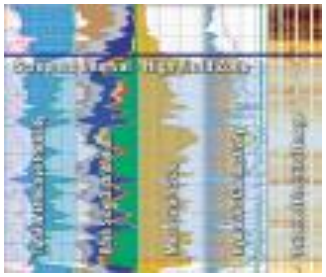
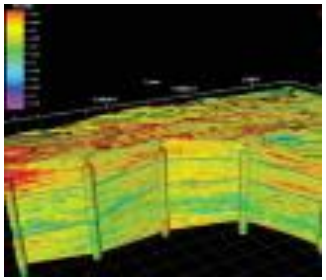
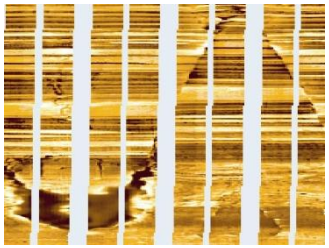
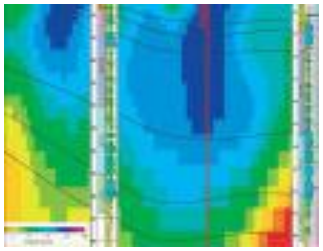
Borehole Geophysical Log Applications









- Optimizing well design
- Improving subsurface conceptual model development
- Characterizing contaminated site complexity
- Characterizing fractured media
- Assessing well integrity
- Constraining surface geophysics

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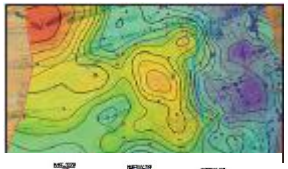
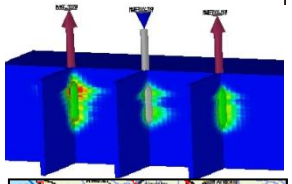
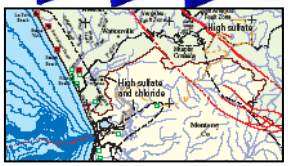
Geophysical Log
Groundwater Solutions



- Water Resources Management



- Aquifer Storage and Recovery (ASR)



- Coastal Zone Groundwater Management

- Water Solutions for Mines

- Environmental Site Solutions

- Groundwater Monitoring

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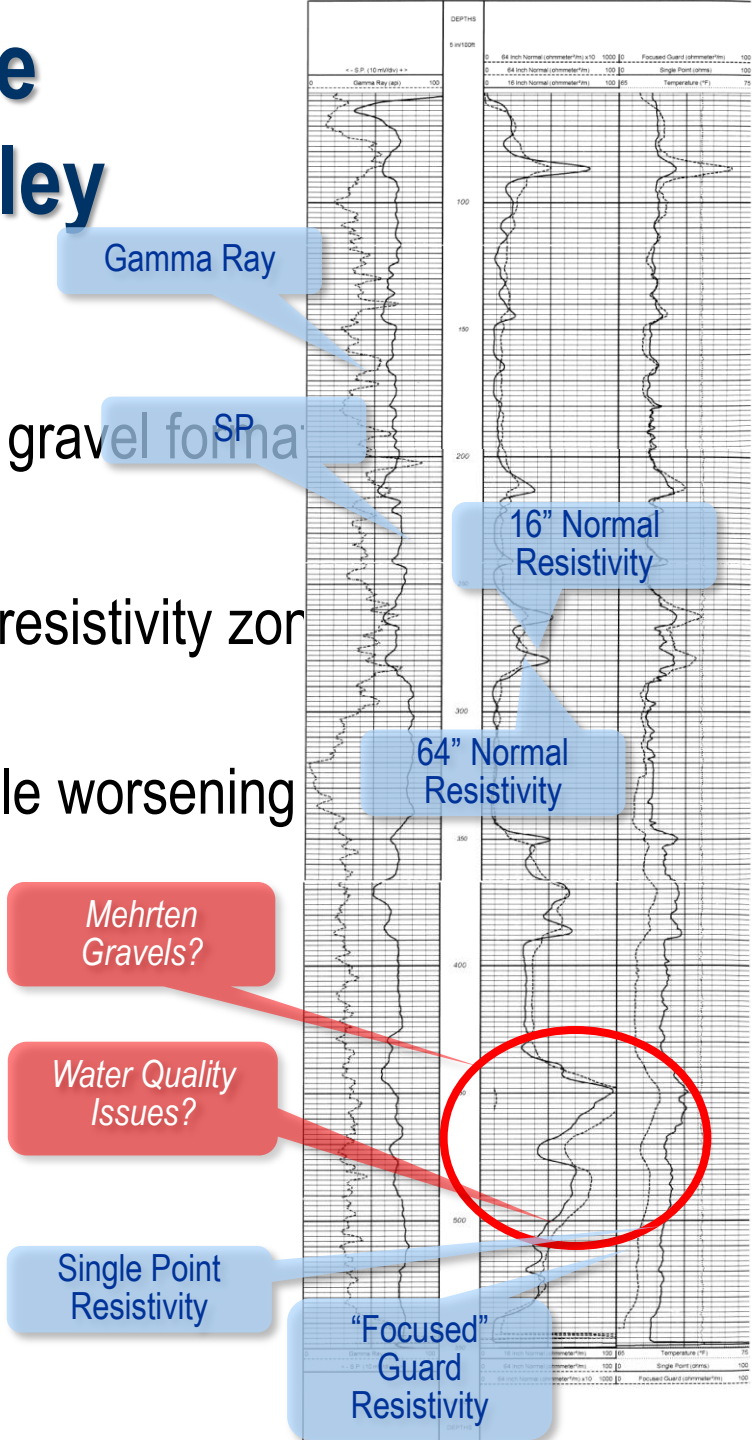
Drilling of ASR Pilot Borehole (17.5-inch) – Sacramento Valley

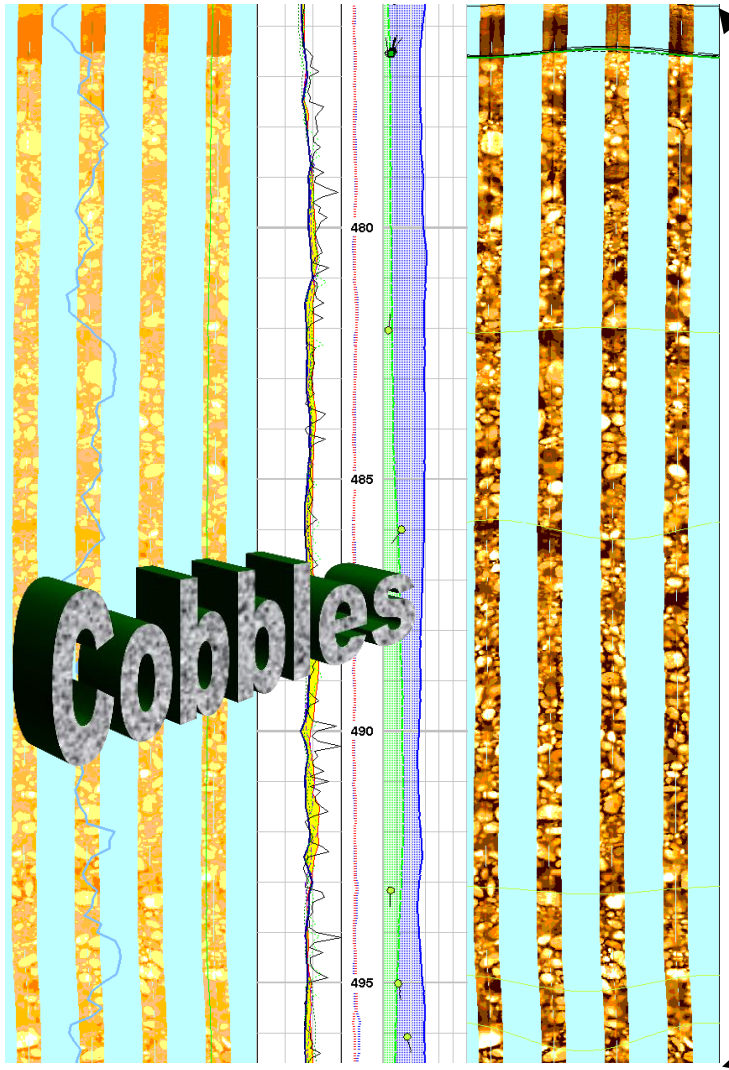
- Problematic drilling
- Drill cuttings don't indicate expected alluvial gravel forma
- Drill cuttings unreliable
- Traditional geophysical logs indicate higher resistivity zor be productive, but qualitative
- Resistivity logs decrease at bottom – possible worsening

QUESTIONS:

- *Will well be productive?*
- *Will there be water quality problems?*
- *How should the well be completed?*



High Resolution Log Results (1)



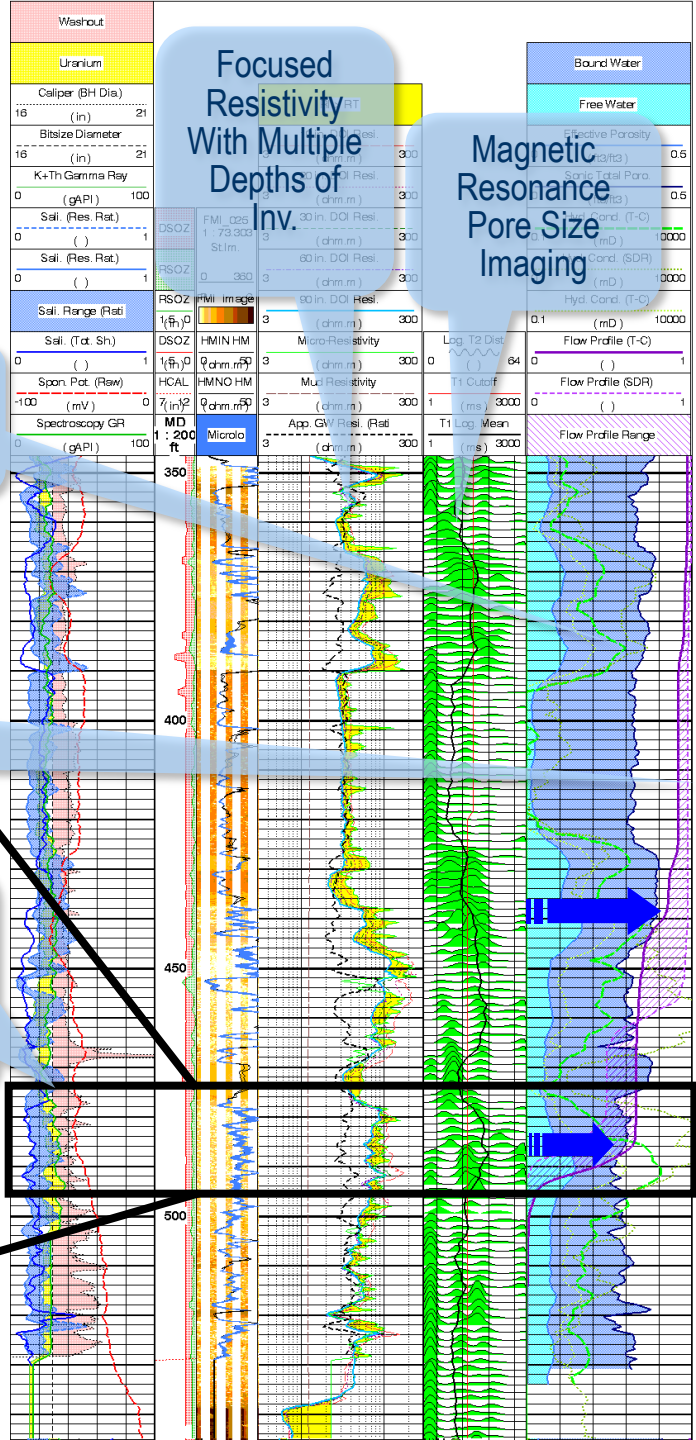
Effective (Light Blue) and Total (Dark Blue) Porosity

Estimated Well Flow Profile (Purple)

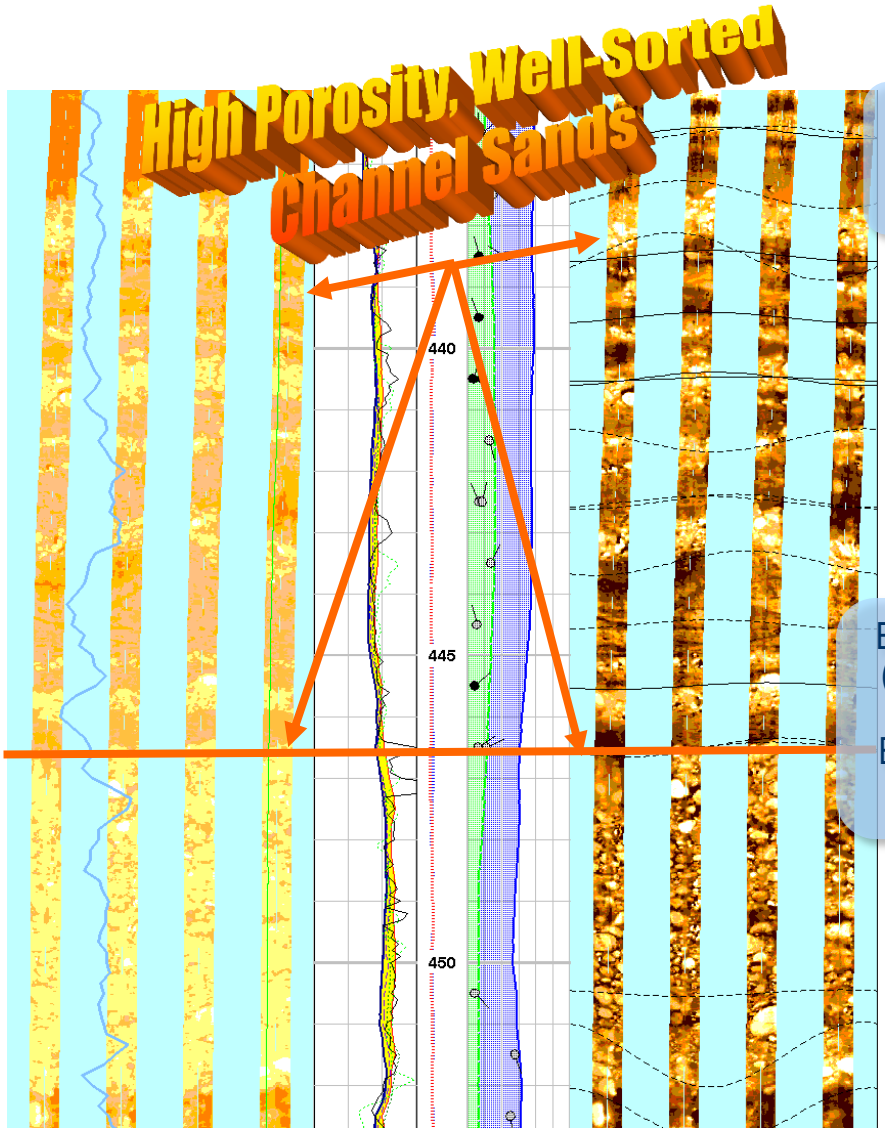
Estimated GW Salinity (Blue) – No Indication of Water Quality at Bottom (less than 350 ppm)

Focused Resistivity With Multiple Depths of Inv.

Magnetic Resonance Pore Size Imaging



High Resolution Log Results (2)



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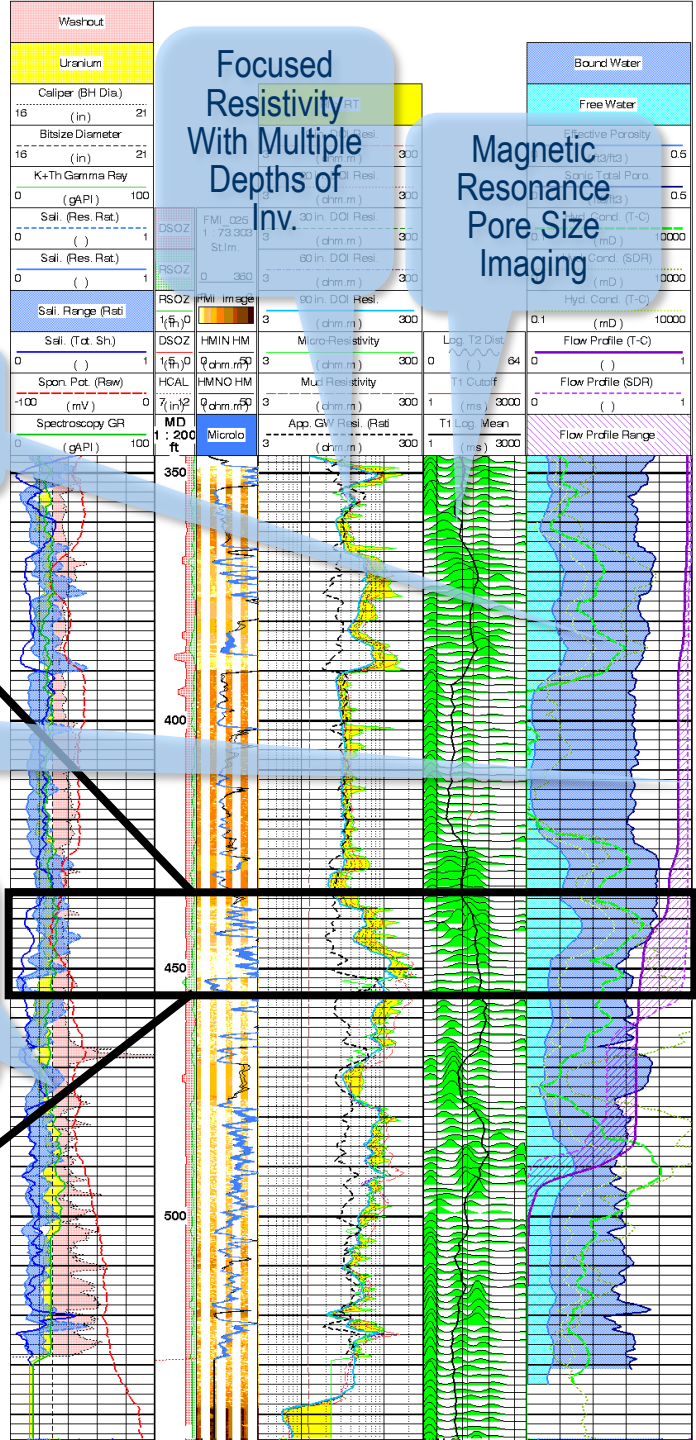
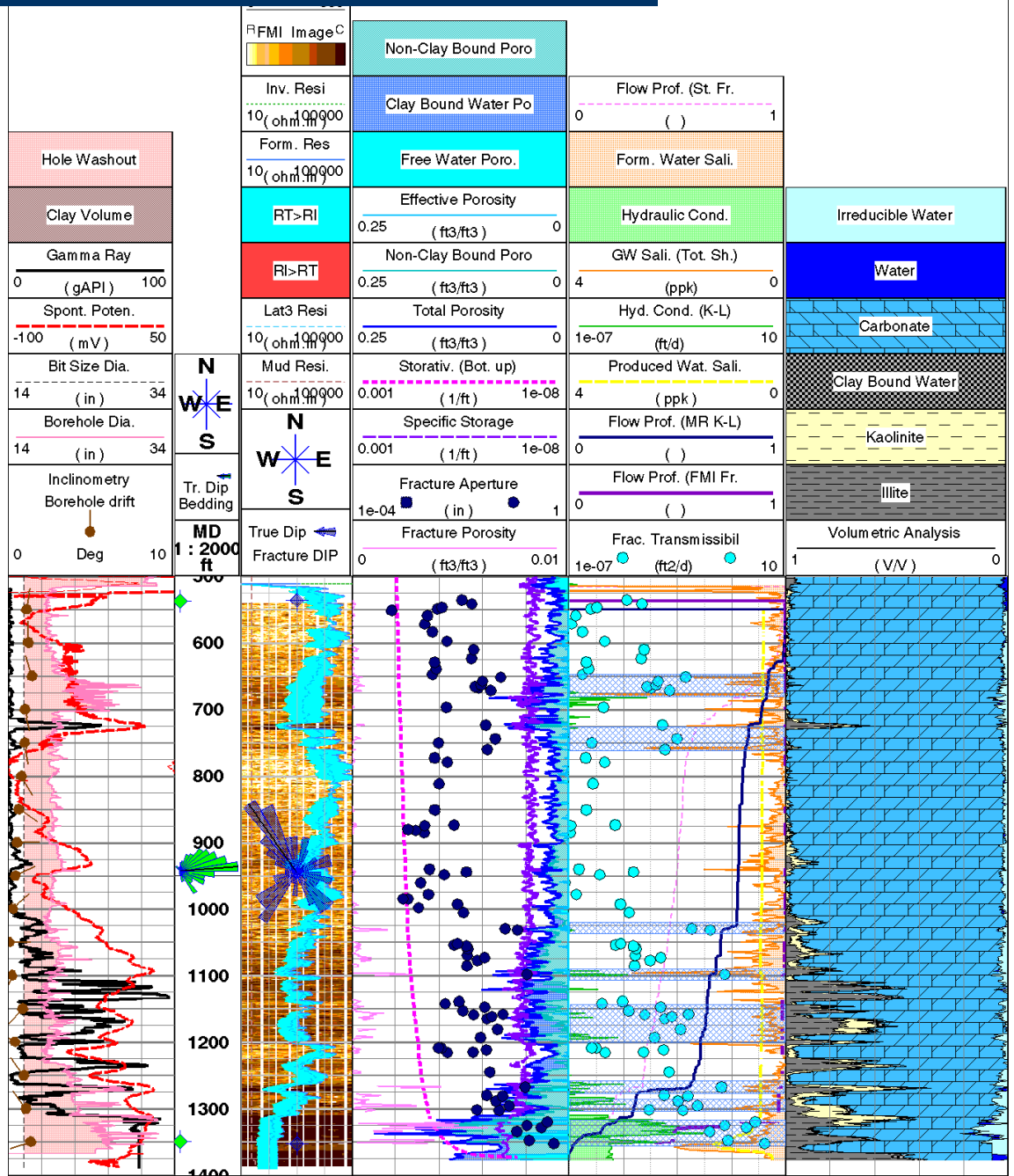


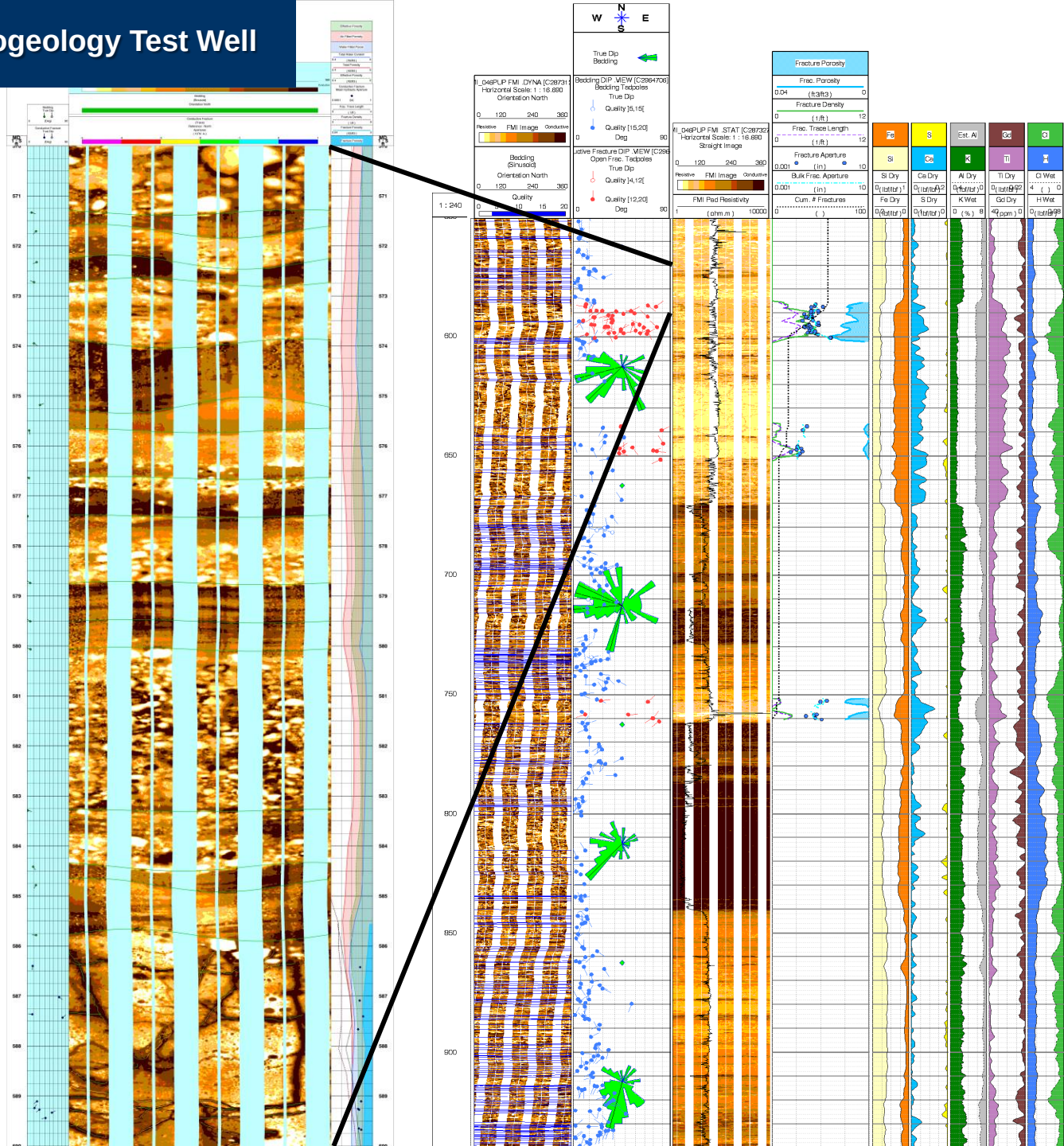
Carbonate Groundwater Resource Investigation: Nevada

- Carbonate bedrock production test well
- Logging suite – focused bulk resistivity, electrical imaging, magnetic resonance, dipole sonic, GR, SP
- Discrete fracture analysis including aperture/transmissibility
- Pre-completion flow profile



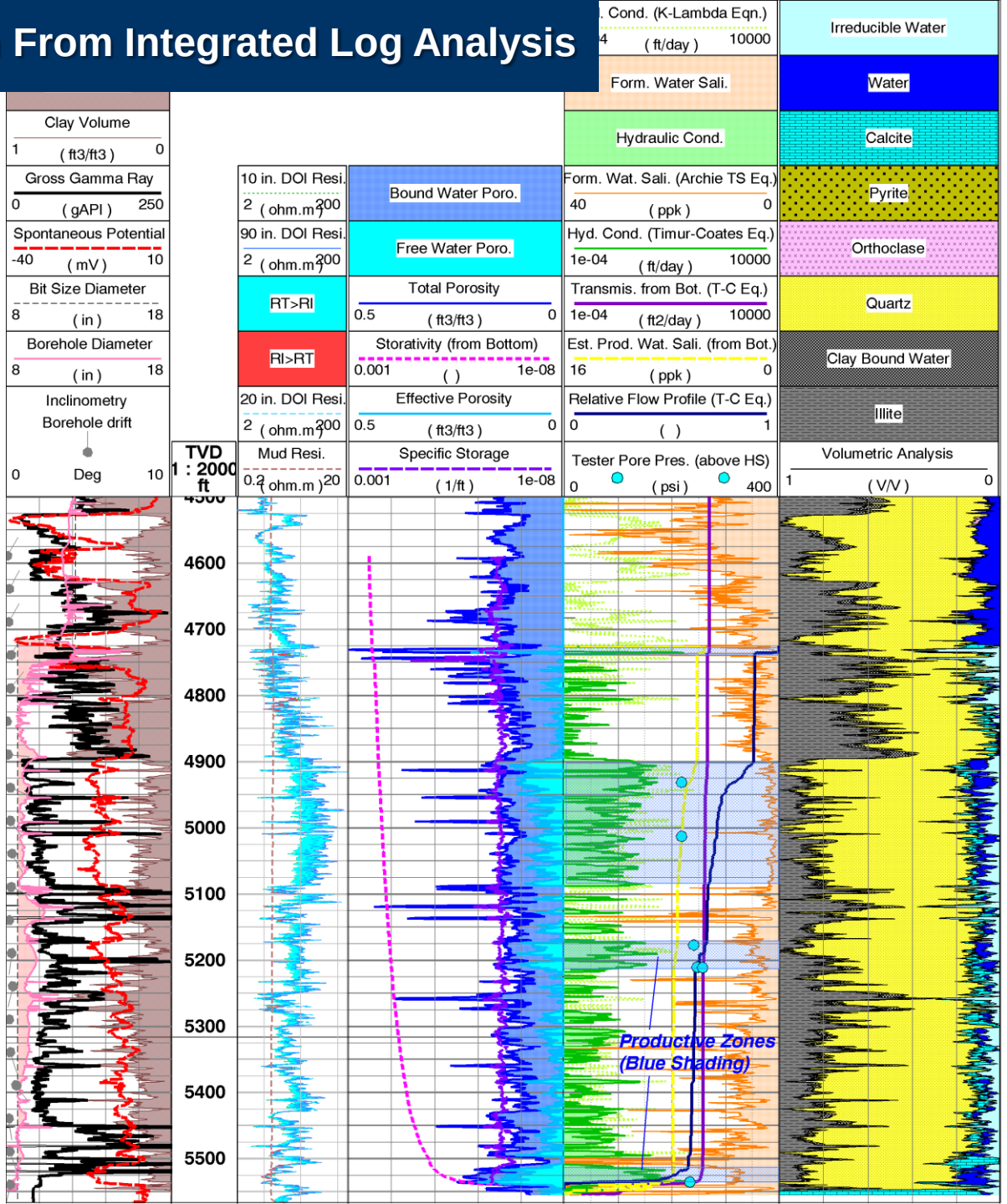
Electrical Image Expanded Scale

- Alluvium + Basalt Interbeds
- High resolution stratigraphy
- Geologic texture and structure
- Discrete fracture evaluation
- Also shown – matrix elemental chemistry from spectroscopy logs



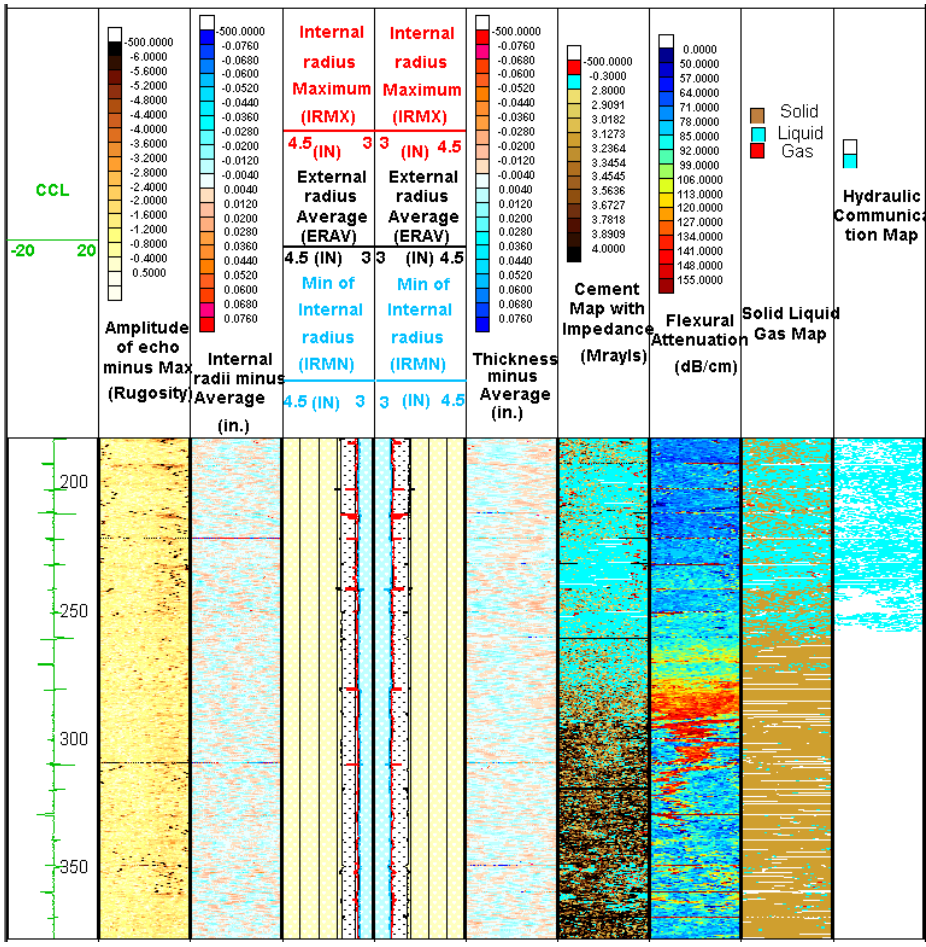
Deep Aquifer Characterization From Integrated Log Analysis

- Water resource investigation for power plant in the Southwest
- Logging suite:
  magnetic resonance, litho-density, neutron porosity, array induction, dipole sonic, packer-probe hydraulic tester, neutron-gamma elemental spectroscopy
- 60% of production potential from 20 ft. zone below 5500 ft
- Highly artesian aquifers at depth (250 psi over hydrostatic)
- Low to moderate salinity
- Very high GR peaks in bottom productive zone – potential radioisotope problem



Key Logging Technologies – Well Integrity

- **Sonic Cement Bond Log**
  - Non-directional cement bond to casing
  - Non-directional indication of cement bond to rock
  - *Blank steel casing only, cement only, fluid-filled*
- **Ultrasonic Imaging** *(21 in. max casing)*
  - High resolution, directional casing thickness and inner wall radius
  - High resolution, directional cement bond to casing (including channeling and material behind casing)
  - *Steel casing only, fluid-filled*
- **Electromagnetic Inspection Log** *(13 in. max casing)*
  - High resolution, directional casing corrosion properties, including dual casing (thickness, weight)
  - *Steel casing only*
- **Gravel Pack Log**
  - Annular fill composition
  - Voids detection



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Value of Advanced Geophysical Logging

High quality borehole geophysical logs can provide quantitative information on:

- Fine-scale variation in porosity and permeability/heterogeneity
- Pore and grain size distribution
- Secondary porosity (type and orientation)
- Sedimentary features, geologic structure
- Fracture systems (fracture orientation, aperture, sets, intensity, porosity)
- Geochemistry & mineralogy (e.g. pyrite concentration)
- Pore water chemistry (discrete depth sampling, TDS, chlorinity)

Quantitative well completion evaluation

- Production profile (inflow/outflow, annular flow)
- Casing/screen condition (steel thickness/corrosion, geometry)
- Annular fill condition (material placement, voids, cement bond)

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Choice of Geophysical Logging Tool Suite Depends On…

Project objectives

- Hydrogeologic characterization (hydro-stratigraphy, physical properties, water quality)
- Contaminant characterization (chemical properties)
- Geotechnical characterization (geomechanical properties)
- Monitoring changes in physical/chemical properties (e.g., moisture content, contaminant concentration) – time-lapse monitoring

Borehole/well conditions

- Open or cased, diameter, washouts/rugosity
- Borehole/well fluid type (water-based mud, air, foam)
- Casing type, annular fill material and thickness

Geologic/hydrologic environment

- Clastic, carbonate (karstic?), hard rock, fractured

Regulations – radioactive sources (most licenses prohibit using chemical sources in wells where potable aquifers are not sealed off), required decon of tools, contaminants

Cost vs. value of information (typical conventional logging suite ~$5k, advanced logging suite $25k, cost of production well in U.S. Southwest > $500k)

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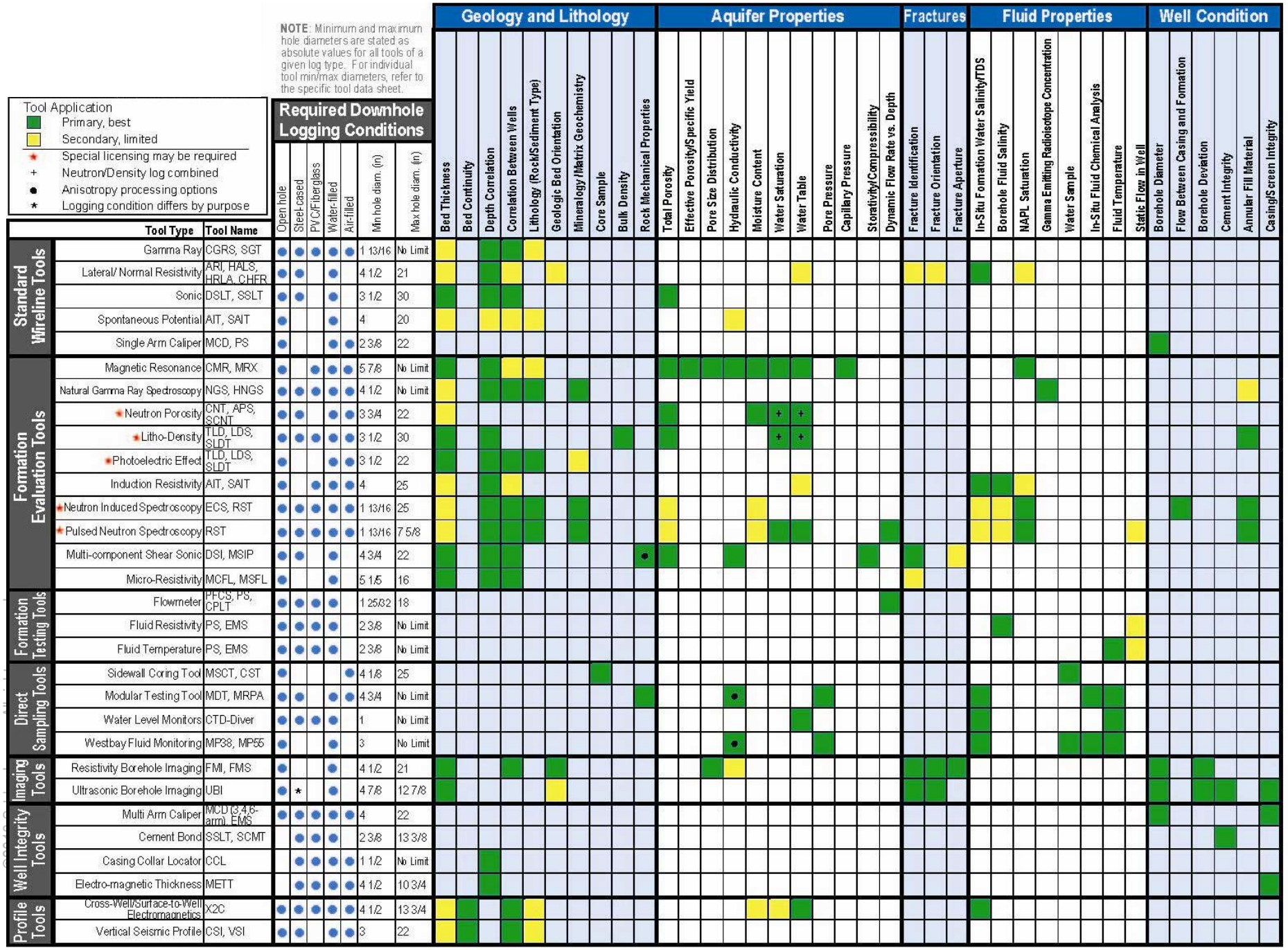
Tool Application
Primary, best
Secondary, limited
Special licensing may be required
Neutron/Density log combined
Anisotropy processing options
Logging condition differs by purpose
NOTE: Minimum and maximum hole diameters are stated as absolute values for all tools of a given log type. For individual tool min/max diameters, refer to the specific tool data sheet.
Required Downhole Logging Conditions
Geology and Lithology
Aquifer Properties
Fractures
Fluid Properties
Well Condition
Tool Type
Tool Name
Open hole
Steel-cased
PVC/Fiberglass
Water-filled
Air-filled
Min hole diam. (in)
Max hole diam. (in)
Bed Thickness
Bed Continuity
Depth Correlation
Correlation Between Wells
Lithology (Rock/Sediment Type)
Geologic Bed Orientation
Mineralogy/Matrix Geochemistry
Core Sample
Bulk Density
Rock Mechanical Properties
Total Porosity
Effective Porosity/Specific Yield
Pore Size Distribution
Hydraulic Conductivity
Moisture Content
Water Saturation
Water Table
Pore Pressure
Capillary Pressure
Storativity/Compressibility
Dynamic Flow Rate vs. Depth
Fracture Identification
Fracture Orientation
Fracture Aperture
In-Situ Formation Water Salinity/TDS
Borehole Fluid Salinity
NAPL Saturation
Gamma Emitting Radioisotope Concentration
Water Sample
In-Situ Fluid Chemical Analysis
Fluid Temperature
Static Flow in Well
Borehole Diameter
Flow Between Casing and Formation
Borehole Deviation
Cement Integrity
Annular Fill Material
Casing/Screen Integrity
Standard Wireline Tools
Gamma Ray CGRS, SGT 1 13/16 No Limit
Lateral/ Normal Resistivity ARI, HALS, HRLA, CHFR 4 1/2 21
Sonic DSLT, SSLT 3 1/2 30
Spontaneous Potential AIT, SAIT 4 20
Single Arm Caliper MCD, PS 2 3/8 22
Formation Evaluation Tools
Magnetic Resonance CMR, MRX 5 7/8 No Limit
Natural Gamma Ray Spectroscopy NGS, HNGS 4 1/2 No Limit
Neutron Porosity CNT, APS, SCNT 3 3/4 22
Litho-Density TLD, LDS, SLDT 3 1/2 30
Photoelectric Effect TLD, LDS, SLDT 3 1/2 22
Induction Resistivity AIT, SAIT 4 25
Neutron Induced Spectroscopy ECS, RST 1 13/16 25
Pulsed Neutron Spectroscopy RST 1 13/16 7 5/8
Multi-component Shear Sonic DSI, MSIP 4 3/4 22
Micro-Resistivity MCFL, MSFL 5 1/5 16
Formation Testing Tools
Flowmeter PFCS, PS, CPLT 1 25/32 18
Fluid Resistivity PS, EMS 2 3/8 No Limit
Fluid Temperature PS, EMS 2 3/8 No Limit
Direct Sampling Tools
Sidewall Coring Tool MSCT, CST 4 1/8 25
Modular Testing Tool MDT, MRPA 4 3/4 No Limit
Water Level Monitors CTD-Diver 1 No Limit
Westbay Fluid Monitoring MP38, MP55 3 No Limit
Imaging Tools
Resistivity Borehole Imaging FMI, FMS 4 1/2 21
Ultrasonic Borehole Imaging UBI 4 7/8 12 7/8
Well Integrity Tools
Multi Arm Caliper MCD (3,4,6-arm), EMS 4 22
Cement Bond SSLT, SCMT 2 3/8 13 3/8
Casing Collar Locator CCL 1 1/2 No Limit
Electro-magnetic Thickness METT 4 1/2 10 3/4
Profile Tools
Cross-Well/Surface-to-Well Electromagnetics X2C 4 1/2 13 3/4
Vertical Seismic Profile CSI, VSI 3 22