General Introduction to Well Logging

International School on Geothermal Exploration
1^{st} Dec 2011

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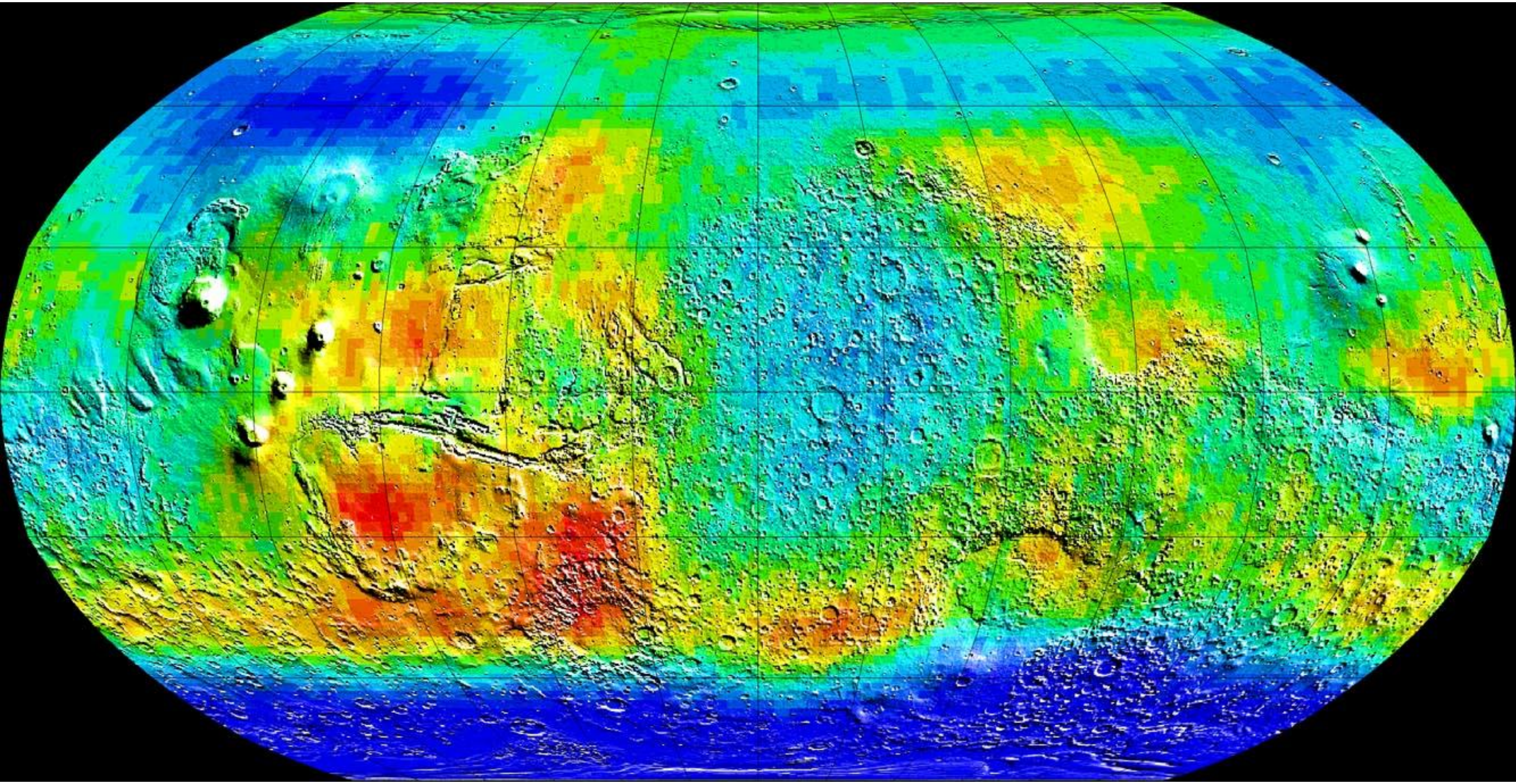
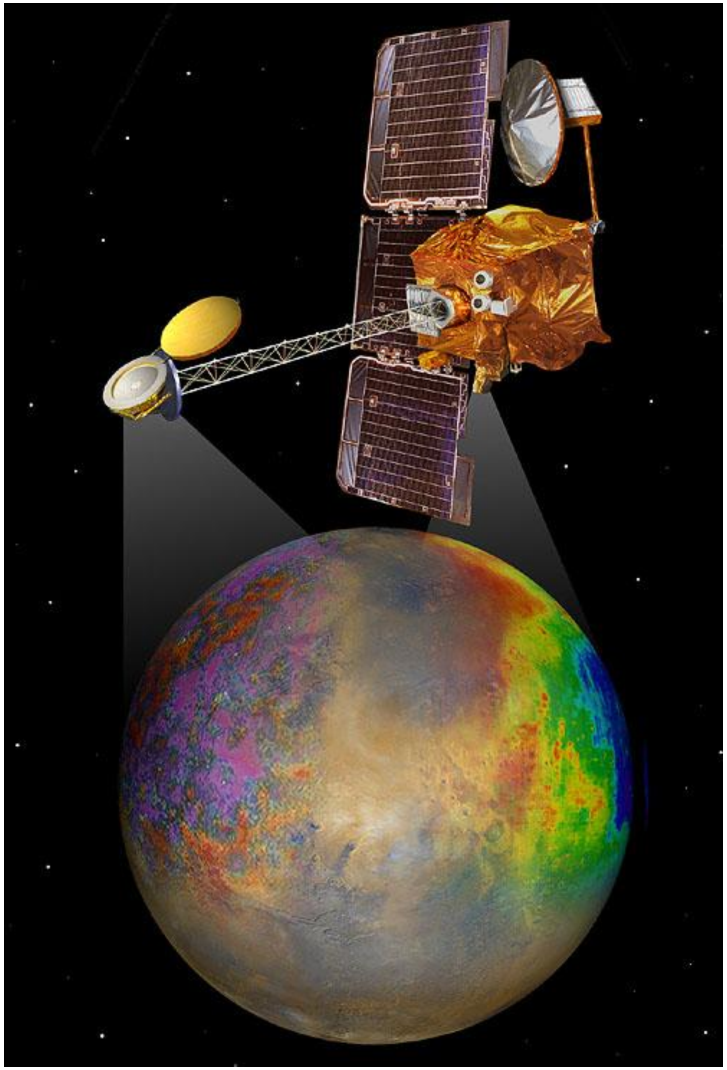
Schlumberger

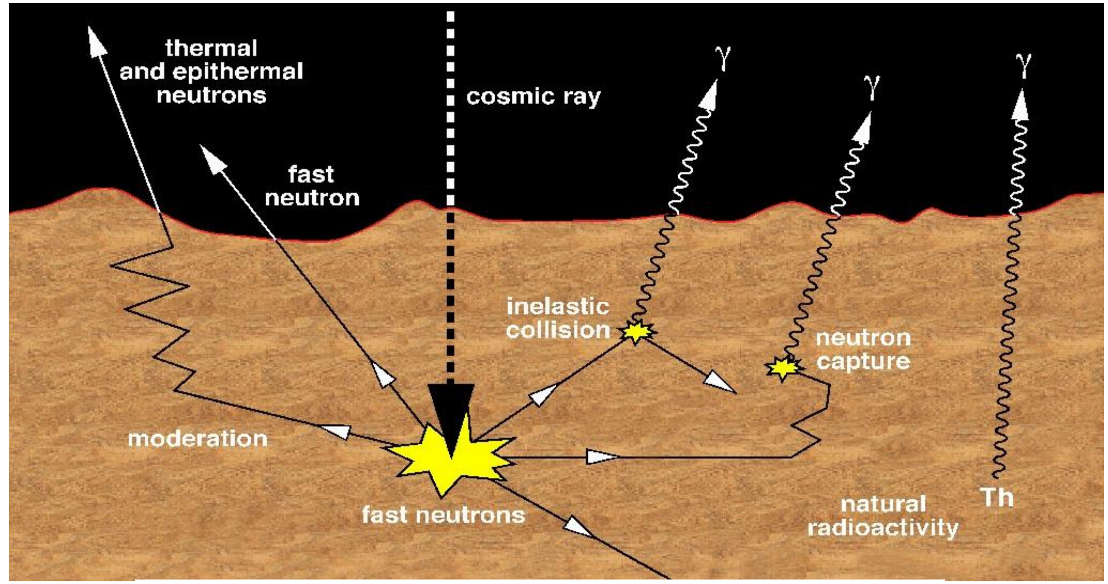
Global Map of Epithermal Neutrons on Mars

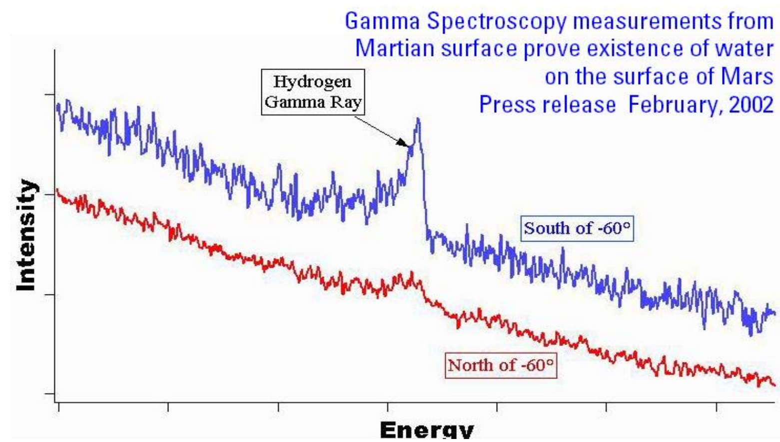


Courtesy: NASA/JPL/Caltech

2001 Mars Odyssey Mission
Gamma Ray Spectrometer Measurements







Courtesy: NASA/JPL/Caltech

Challenge Here on Earth

- Usually Cannot Directly Measure the Quantity we Want
- Must Use Available Techniques to Estimate the Quantities
- For Example
  - Lithology (Rock Types)
  - Porosities
  - Fluid Saturations
  - Permeability

Well Logging and Petrophysics

Petrophysics is the study of the physical and chemical properties that describe the occurrence and behavior of rocks, soils and fluids.

Goals

- To identify and quantify hydrocarbon content,
- evaluate fluid & rock properties
- To describe and predict reservoir behavior

Archie's Equation (SPE942054)

The Electrical Resistivity Log as an Aid in Determining Some Reservoir Characteristics

By G. E. Archie*

(Dallas Meeting, October 1941)

$$Sw^n = \frac{aRw}{\phi^m Rt}$$

a : is the local correction factor
m : is the cementation exponent
n : is the saturation exponent

Relates Porosity, Conductivity, and Brine Saturation of Rocks
But in Clean Formations Only

Summary of Resistivity Based Sw

$$Sw = f(Rt, \phi)$$

↑ Rt

Hydrocarbon Saturation ↑

Other Popular Water Saturation Methods

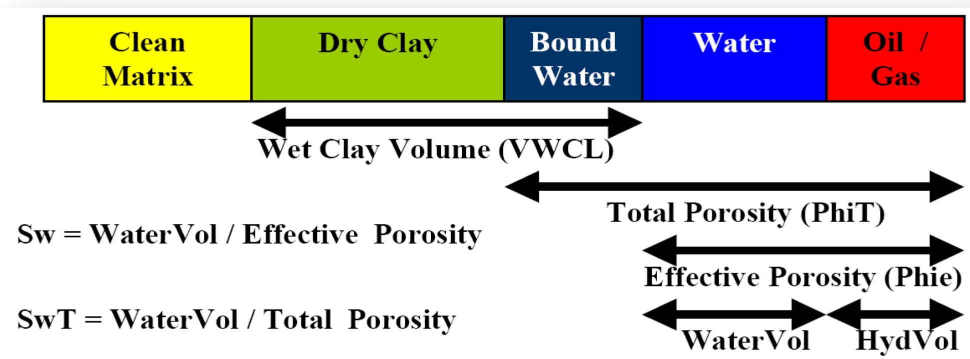
- Indonesian (Poupon-Leveaux)
- Simandoux
- Dual Water

$$\frac{1}{\sqrt{Rt}} = \left(\sqrt{\frac{\phi^m}{a \times Rw}} + \frac{Vcl^{(1-Vcl/2)}}{\sqrt{Rcl}}\right) \times Sw^{n/2}$$

$$\frac{1}{Rt} = \frac{\phi^m \times Sw^n}{a \times Rw} + \frac{Vcl \times Sw}{Rcl}$$

$$\frac{1}{Rt} = \frac{\phi_T^m \times SwT^n}{a} \times \left(\frac{1}{Rw} + \frac{Swb}{SwT}\left(\frac{1}{Rwb} - \frac{1}{Rw}\right)\right)$$

$$Swb = 1 - \frac{\phi_e}{\phi_t}$$



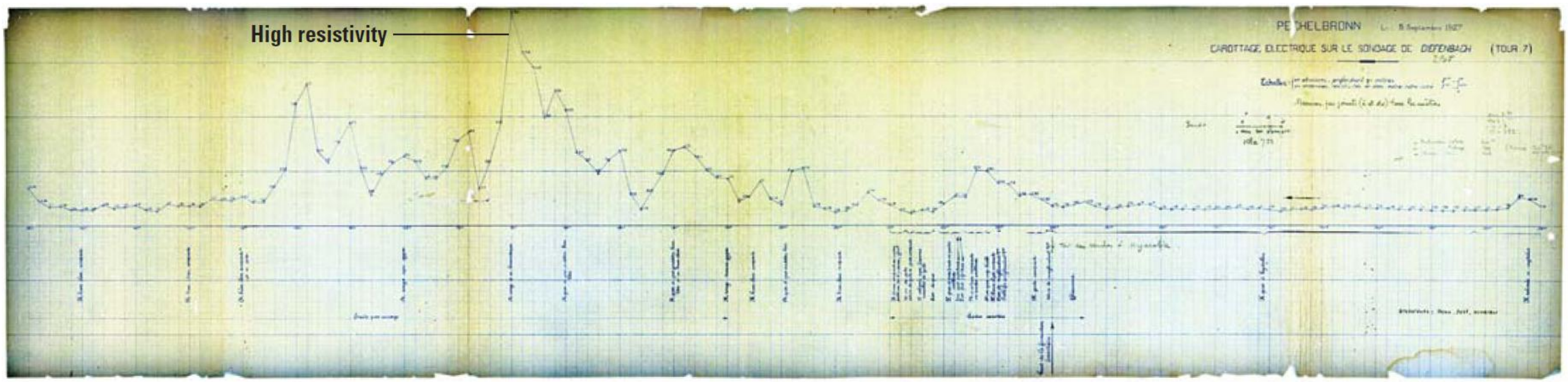
Logging Response Example of Sedimentary Minerals

Name	Formula	ρ_{log} (g/cm^3)	ϕ_{SNP} (p.u.)	ϕ_{CNL} (p.u.)	ϕ_{APS}† (p.u.)	Δt_c ($\mu s/ft$)	Δt_s ($\mu s/ft$)	Pe	U	ε (farad/m)	t_p (ns/m)	Gamma Ray (gAPI Units)	Σ (c.u.)
Silicates													
Quartz	SiO_2	2.64	−1	−2	−1	56.0	88.0	1.8	4.8	4.65	7.2		4.3
β-cristobalite	SiO_2	2.15	−2	−3				1.8	3.9				3.5
Opal (3.5% H_2O)	$SiO_2 (H_2O)_{0.1209}$	2.13	4	2		58		1.8	3.7				5.0
Garnet‡	$Fe_3Al_2(SiO_4)_3$	4.31	3	7				11	48				45
Hornblende‡	$Ca_2NaMg_2Fe_2AlSi_8O_{22}(O,OH)_2$	3.20	4	8		43.8	81.5	6.0	19				18
Tourmaline	$NaMg_3Al_6B_3Si_6O_2(OH)_4$	3.02	16	22				2.1	6.5				7450
Zircon	$ZrSiO_4$	4.50	−1	−3				69	311				6.9
Carbonates													
Calcite	$CaCO_3$	2.71	0	0	0	49.0	88.4	5.1	13.8	7.5	9.1		7.1
Dolomite	$CaCO_3MgCO_3$	2.85	2	1	1	44.0	72	3.1	9.0	6.8	8.7		4.7
Ankerite	$Ca(Mg,Fe)(CO_3)_2$	2.86	0	1				9.3	27				22
Siderite	$FeCO_3$	3.89	5	12	3	47		15	57	6.8–7.5	8.8–9.1		52
Clays‡													
Kaolinite	$Al_4Si_4O_{10}(OH)_8$	2.41	34	~37	~34			1.8	4.4	~5.8	~8.0	80–130	14
Chlorite	$(Mg,Fe,Al)_6(Si,Al)_4O_{10}(OH)_8$	2.76	37	~52	~35			6.3	17	~5.8	~8.0	180–250	25
Illite	$K_{1-1.5}Al_4(Si_{7-6.5},Al_{1-1.5})O_{20}(OH)_4$	2.52	20	~30	~17			3.5	8.7	~5.8	~8.0	250–300	18
Montmorillonite	$(Ca,Na)_7(Al,Mg,Fe)_4(Si,Al)_8O_{20}(OH)_4(H_2O)_n$	2.12		~60	~60			2.0	4.0	~5.8	~8.0	150–200	14

Inventors of Well Logging: Conrad and Marcel Schlumberger

In 1912 Conrad Schlumberger, using very basic equipment, recorded the first map of equipotential curves in his Normandy estate near Caen.

First Well Log Sept 5, 1927, Pechelbronn France



Challenges Explained by a Log "Header"

COMPANY:	**My Oil Company**
WELL:	**P-1**
FIELD:	**P**
LOCATION:	**LAND**

Country:
Field: P
Location: 526754 E 6785651
Well: N
Company:

Schlumberger

DUAL INDUCTION / DENSITY / NEUTRON MICROLOG / GAMMA RAY

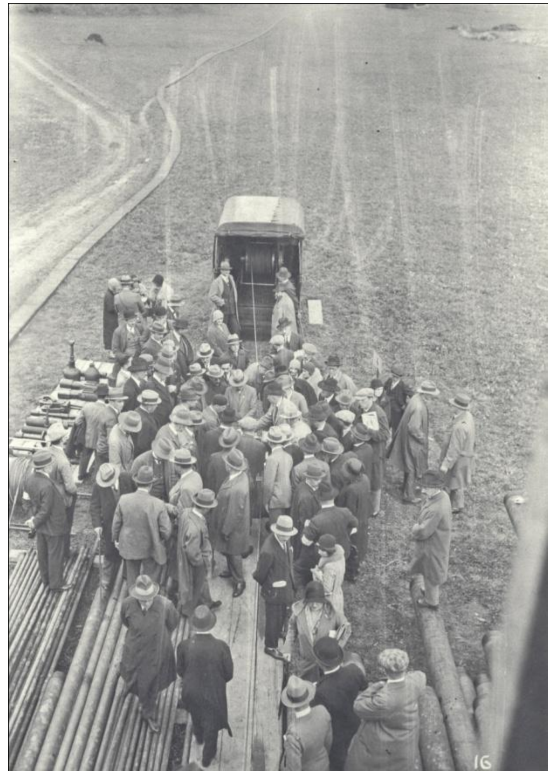
LOCATION

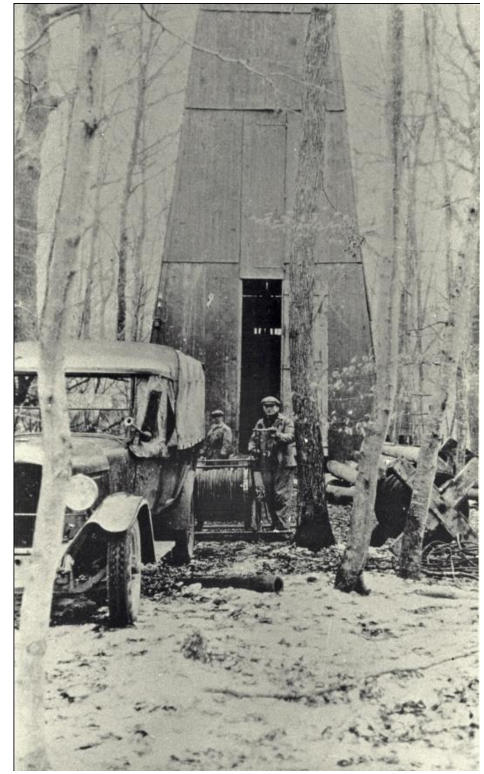
			Elev.:	K.B.	
				G.L.	0.0 M
				D.F.	12.0 M
Permanent Datum:	MSL		Elev.:	1.3 M	
Log Measured From:	DRT	10.7 M	above Perm. Datum		
Drilling Measured From:	DRT				

API serial No.	SECTION	TOWNSHIP	RANGE
12-123-123456			

Logging Date	9 DEC 1987	
Run Number	1	
Depth Driller	3334.0 M	
Schlumberger Depth	3338.5 M	
Bottom Log Interval	3337.5 M	
Top Log Interval	2904.0 M	
Casing Driller Size @ Depth	9 5/8" @ 2903.0 M	12 1/4" @ 2001.0 M
Casing Schlumberger	2904.0 M	2001.5 M
Bit Size	8 3/8"	
Type Fluid In Hole	KCL-GYP	
MUD Density / Viscosity	1.22 G/CC / 52.0 S	
Fluid Loss / PH	3.2 C3 / 10.3	
Source of Sample	Flow Line	
RM @ Measured Temperature	0.076 OHMM @ 14.0 DEGC	
RMF @ Measured Temperature	0.060 OHMM @ 14.0 DEGC	
RMC @ Measured Temperature	0.222 OHMM @ 14.0 DEGC	
Source RMF / RMC	Press / Press	
RM @ BHT / RMF @ BHT	0.023 @ 94 / 0.019 @ 94	
Maximum Recorded BHT	94 94 93	
Circulation Stopped	9:00 8/12	
Logger on Bottom	21:58 8/12	
Unit Number / Location	2803 / HOT	
Recorded By	G.Sutherland	
Witnessed By	R.J. Branvold	

Early Days 1920's





Timeline 1920's

1920 | 1930 | 1940 | 1950 | 1960 | 1970 | 1980 | 1990 | 2000 | 2010

1927: first electrical resistivity well log in Pechelbronn, France

1929: first electrical resistivity well log Kern County California

Marcel Schlumberger, far right, in the laboratory at Vitre, Brittany, testing a surface prospecting device used to measure dip.

http://www.slb.com/about/history

Timeline 1930's

1920 | **1930** | 1940 | 1950 | 1960 | 1970 | 1980 | 1990 | 2000 | 2010

1930: continuous-recording hand recorder, enabling plotting of continuous log of information

1931: Spontaneous Potential (SP) log

1932: Conrad and Marcel Schlumberger present the first comprehensive description of the principles of well logging "Electrical Coring: A Method of Determining Bottom-Hole Data by Electrical Measurements."

1936: Sample Taker tool

The basic tool for all Schlumberger field operations, the logging truck, easily recognized by its characteristic blue color adopted in 1936, became an indispensable element of wellsite operations.

http://www.slb.com/about/history

Timeline 1940's

1920 1930 **1940** 1950 1960 1970 1980 1990 2000 2010

1941: SP Dipmeter tool for finding angle of formation dip in borehole 1942

1942: Gus Archie of Shell Oil publishes research underpinning "Archie's Law," key to log interpretation

1946: collar locator to measure changes in magnetic flux at the collar's location

1947: First offshore rigs deployed in the Gulf of Mexico

1949: Microlog tool for measuring mudcake thickness and resistivity near the borehole

Logging truck being deployed for operations on an offshore drilling unit, South China Sea, 1947. The logging truck was substantially modernized, equipped with a winch and an electrical cable capable of operating a wide range of services in deeper and deeper boreholes.

1947: first induction log to help distinguish oil- from water-bearing rock layers when the borehole contains fluid that does not conduct electricity
Begins producing nine-galvanometer R9 recorder for simultaneously displaying multiple logging curves

http://www.slb.com/about/history

Timeline 1950's

1920 1930 1940 **1950** 1960 1970 1980 1990 2000 2010

1950: Laterolog system for focusing currents into thin rock layers

1951: Microlaterolog tool for measuring resistivity near the borehole

1954: Microlog-caliper

1956: first induction-electrical log

1957: first density log, enabling realization of bulk density measurement using gamma ray attenuation

By 1957, printed circuit boards were used to provide electrically conductive pathways between the components of logging systems. The miniaturization of circuit boards for downhole use improved tool reliability by reducing the number of soldered connections in tools. In addition, tool failures in hostile environments decreased because the more rugged components resisted shock, vibration, and temperature extremes.

http://www.slb.com/about/history

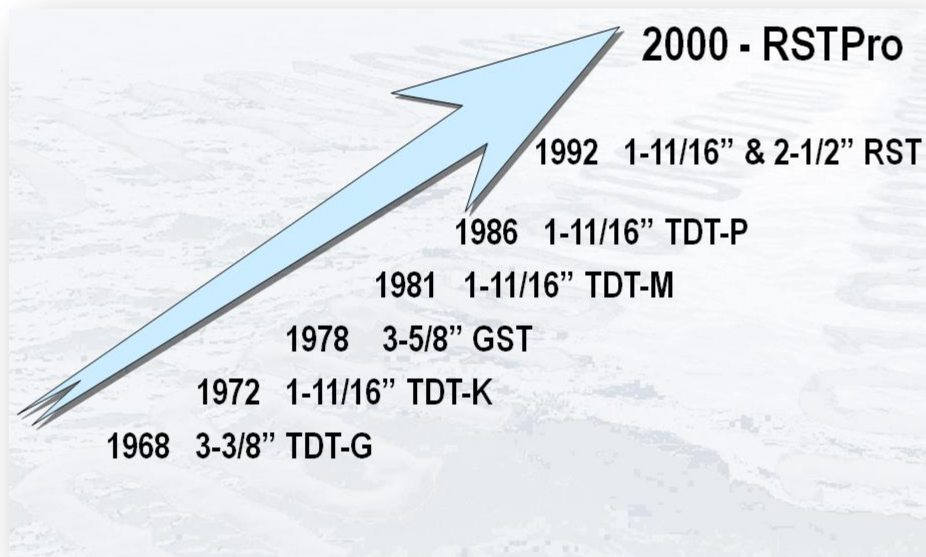
Timeline 1960's

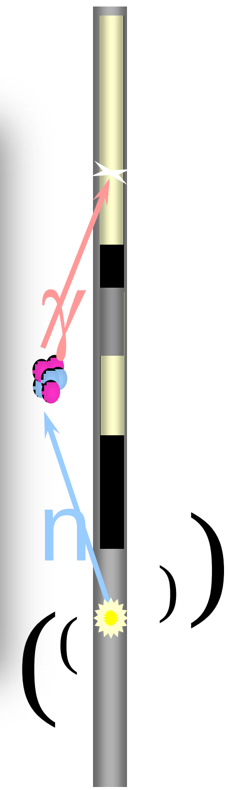
1920 1930 1940 1950 **1960** 1970 1980 1990 2000 2010

1961: first digitized dipmeter logs by computer, marking first successful computer processing of logs from tape

1965: CNL Compensated Neutron Log tool, a two-detector neutron tool for through-casing porosity measurement

1966: Develops small minitron and constructed 1 11/16-in TDT tool for through-tubing production logging





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Timeline 1970's

1920 1930 1940 1950 1960 **1970** 1980 1990 2000 2010

1971: first logging system that combined gamma ray, SP, induction, Spherically Focused Resistivity, sonic, and caliper logs – the "triple combo"

1972: DLL Dual Laterolog tool for simultaneous measurement of shallow region invaded by borehole fluids and the deep undamaged formation

1977: EPT Electromagnetic Propagation Tool, which uses travel time and attenuation of microwave-frequency electromagnetic waves to determine the amount of water in rock pores

1978: SDT tool, the first-generation digital sonic tool for uphole processing of compressional and shear sound speeds in formations

CSU Cabin. Log data could now be transmitted from the field by telephone or satellite. By 1976, the first logging truck equipped with a computer, known as CSU* wellsite surface instrumentation, went into service.

http://www.slb.com/about/history

Timeline 1980's

1920 1930 1940 1950 1960 1970 **1980** 1990 2000 2010

1980: first measurement-while-drilling (MWD) job in the Gulf of Mexico

1982: Crystal graphical log interpretation workstation basis for GeoFrame software

1985: CET Cement Evaluation Tool for adding azimuthal information to cement bond analysis

Formation MicroScanner tool

1988: first logging-while-drilling (LWD) tool

1957: first density log, enabling realization of bulk density measurement using gamma ray attenuation

http://www.slb.com/about/history

Timeline 1990's

1920 1930 1940 1950 1960 1970 1980 **1990** 2000 2010

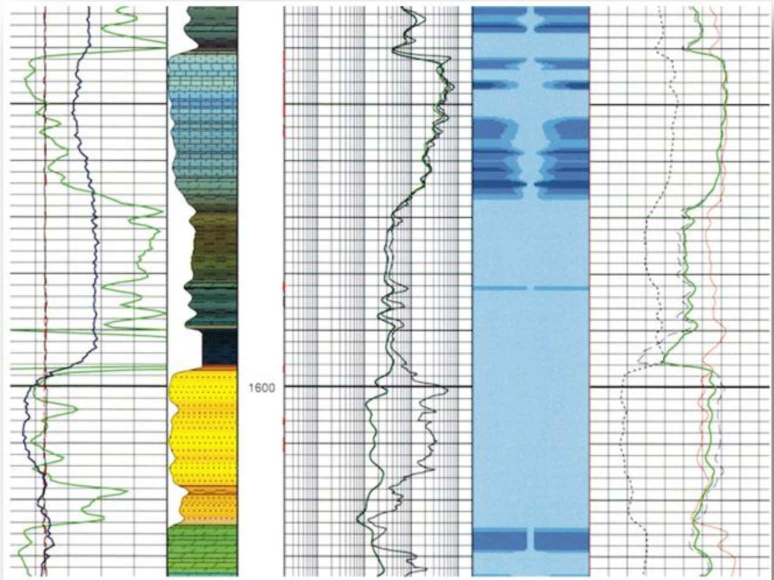
1990: Modular Formation Dynamics Tester commercialized with Optical Fluid Analyzer tool

1991: the FMI Formation MicroImager

1992: the RST Reservoir Saturation Tool

1995: Platform Express technology,, ARC5 LWD tools, and MAXIS Express logging unit
CMR Combinable Magnetic Resonance tool
RST Reservoir Saturation Tool

1998: PS PLATFORM



Platform Express log, 1995. In addition to supplying new measurements, scientists and engineers improved mature measurements. The Platform Express* service greatly speeds rig-up, logging, calibration and processing of the traditional triple-combo system.

Timeline 2000's

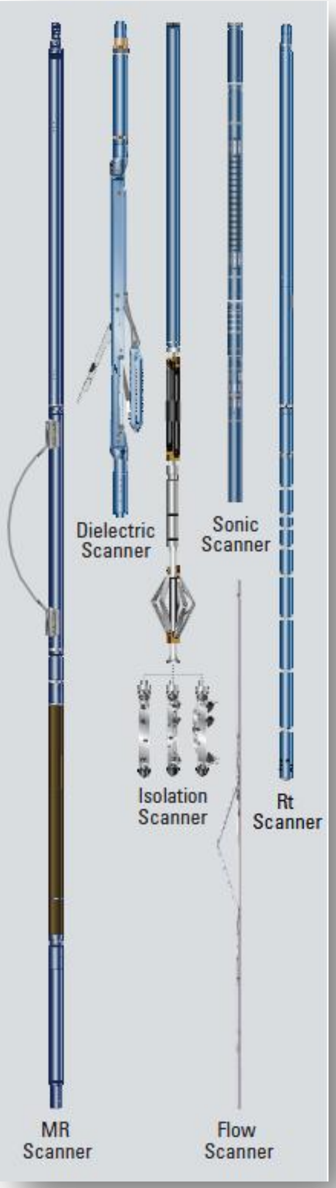
1920 1930 1940 1950 1960 1990 **2000 2010**

2002: ABC Analysis Behind Casing

2005: Scanner downhole rock and fluid characterization services: Rt Scanner multiarray triaxial induction, Sonic Scanner acoustic, and MR Scanner new-generation NMR tools

2006: Quicksilver Probe

2007: InSitu Density sensor



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Well Logging

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Schlumberger

The Intelligent "Mole"

Device that automatically drills a well and finds the pay

(Does not exist)

Picture Courtesy: http://childrenstorytales.com/millie-the-tar-heel-mole/

What's the Problem?

- Nothing Exactly Measures What We Want to Find
- We must use a combination of measurements to interpret Rocks and Fluids
- Getting harder as the easy targets have already been exploited

Land Setup

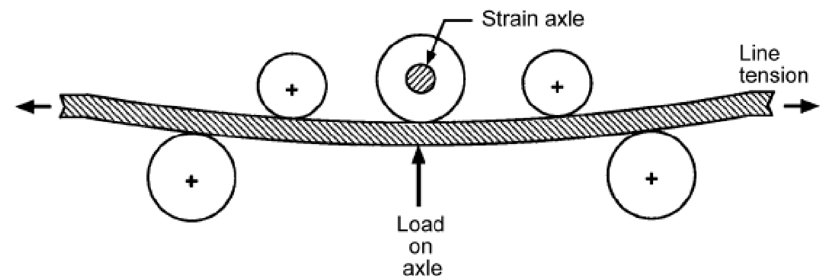
Logging Acquisition System

Offshore Environment

Heli-Transportable Equipment

Logging Cable

Logging Depth and Tension



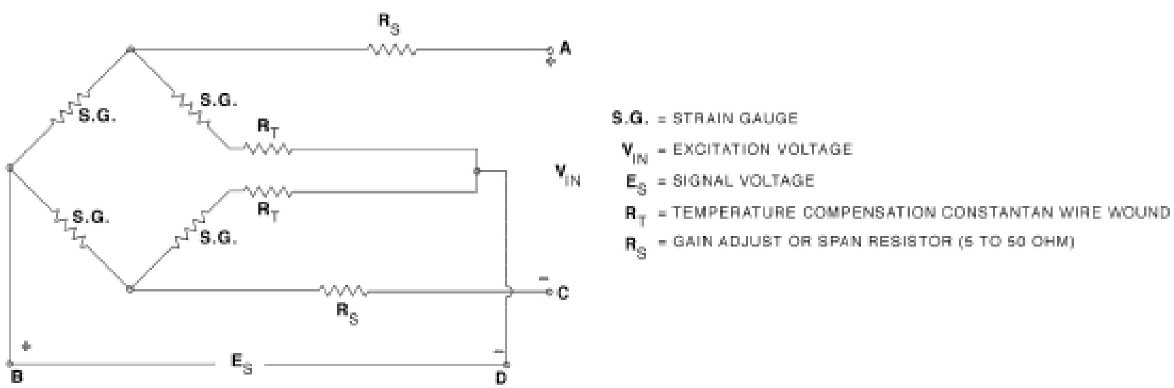
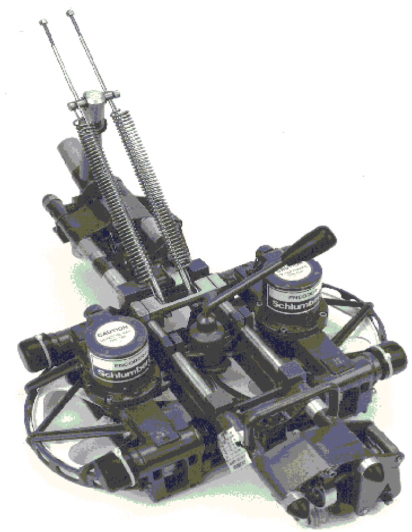
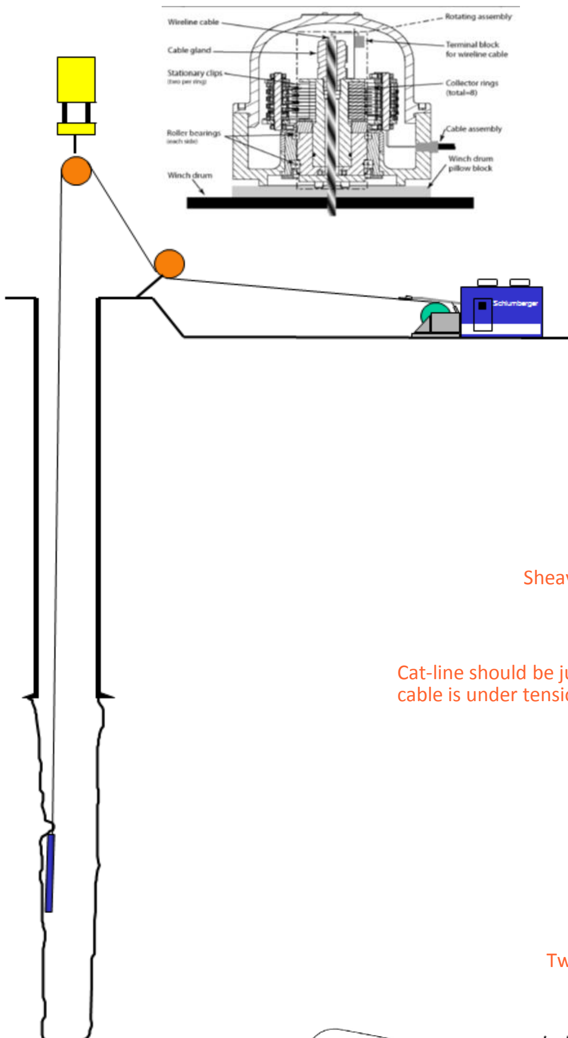
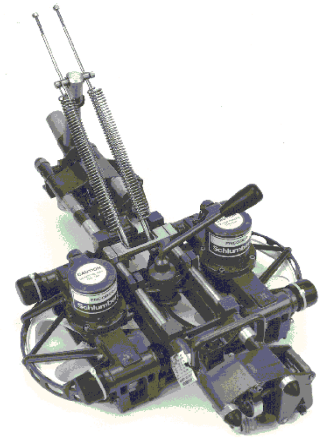


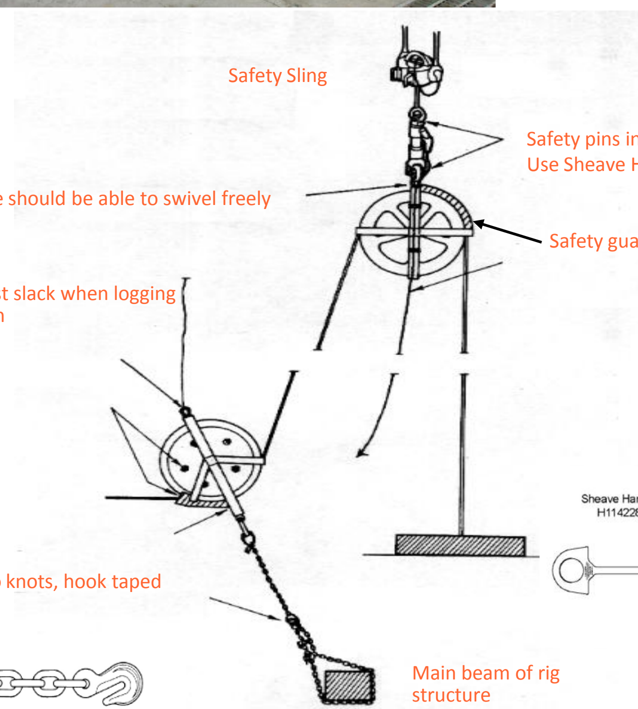
Figure 3-2: Strain axle circuit

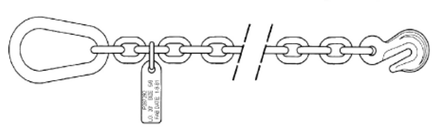


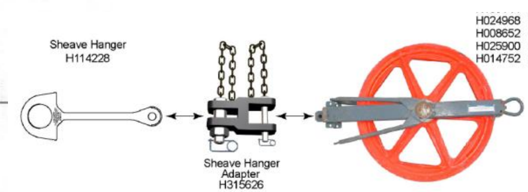
Unit and Rig Up Equipment







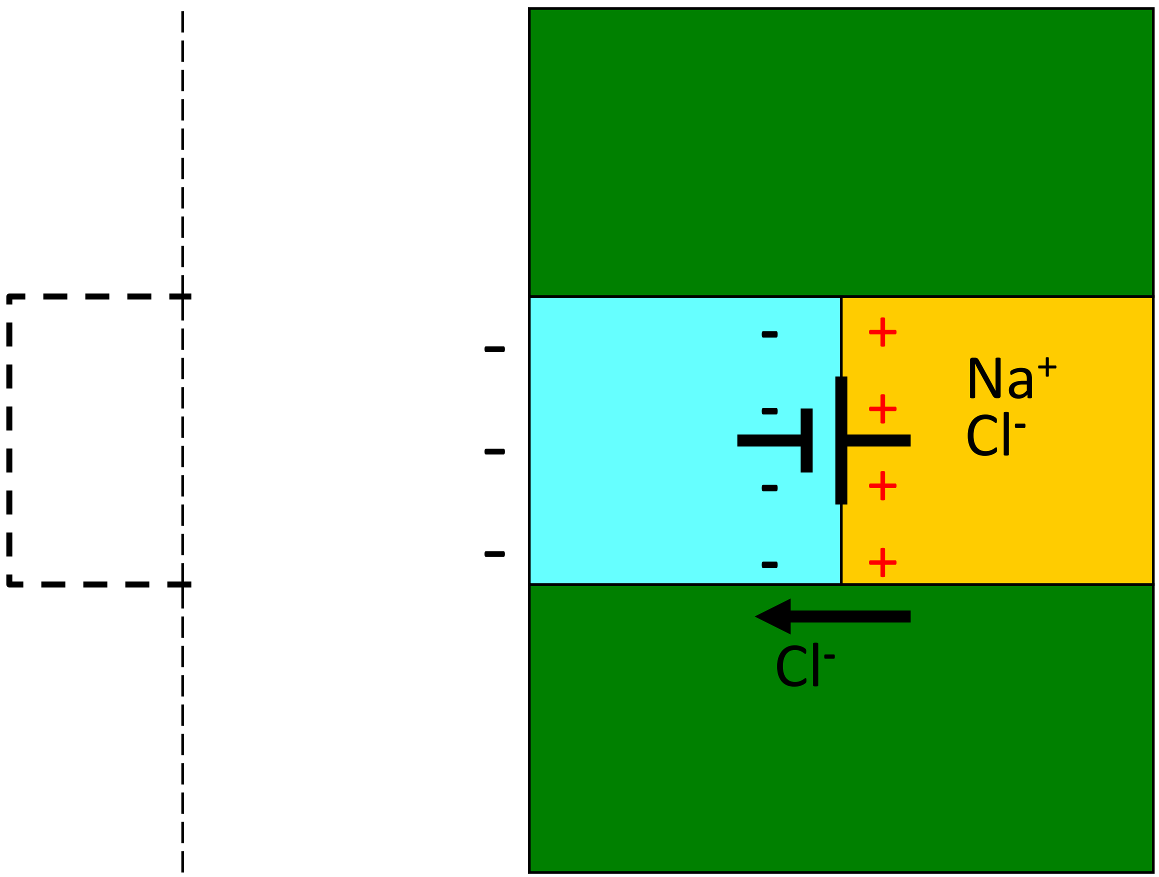




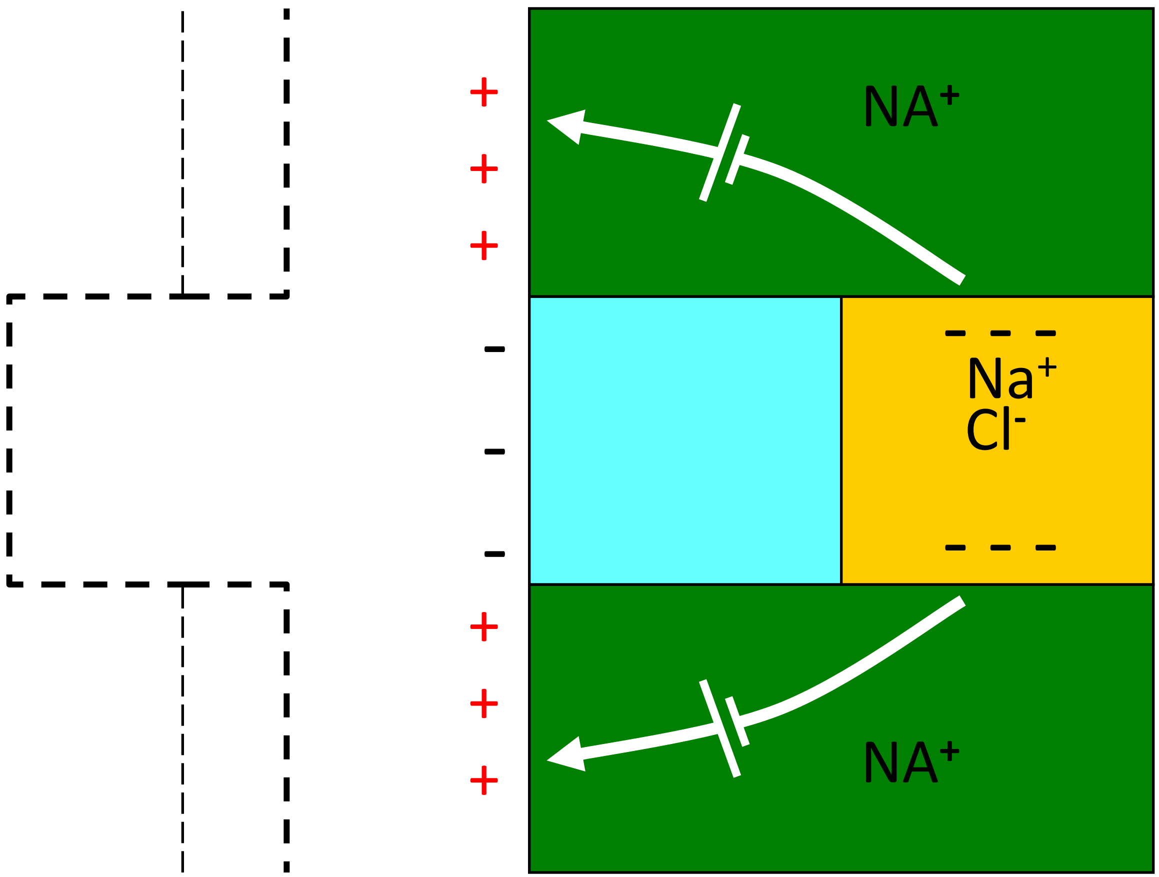
Spontaneous Potential

- Electrochemical
  - **Membrane Potential - Em**
  - **Liquid Junction Potential - Ej**
- Electrokinetic
  - Electrokinetic potential - E_k

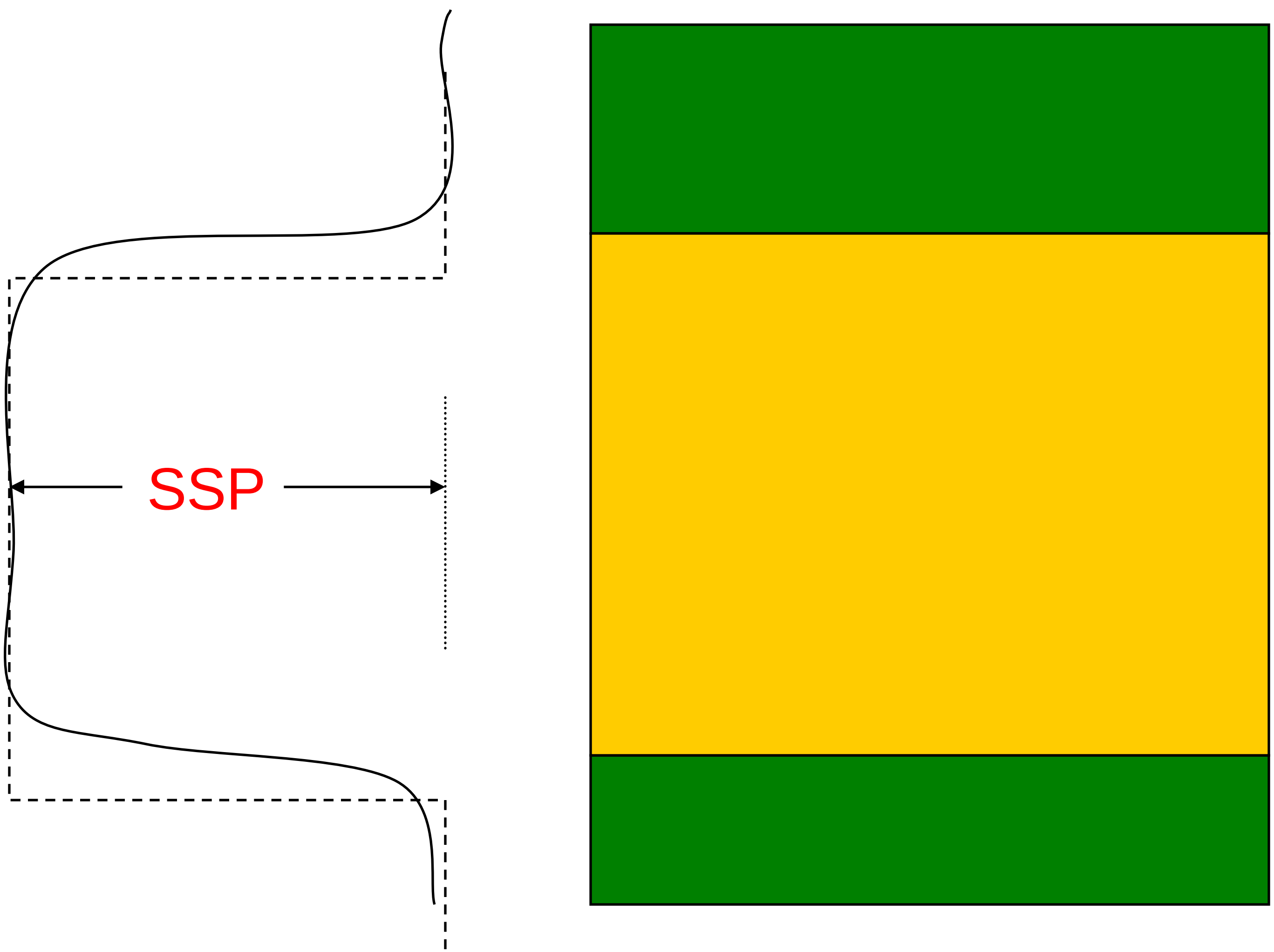
Liquid Junction



Membrane Potential



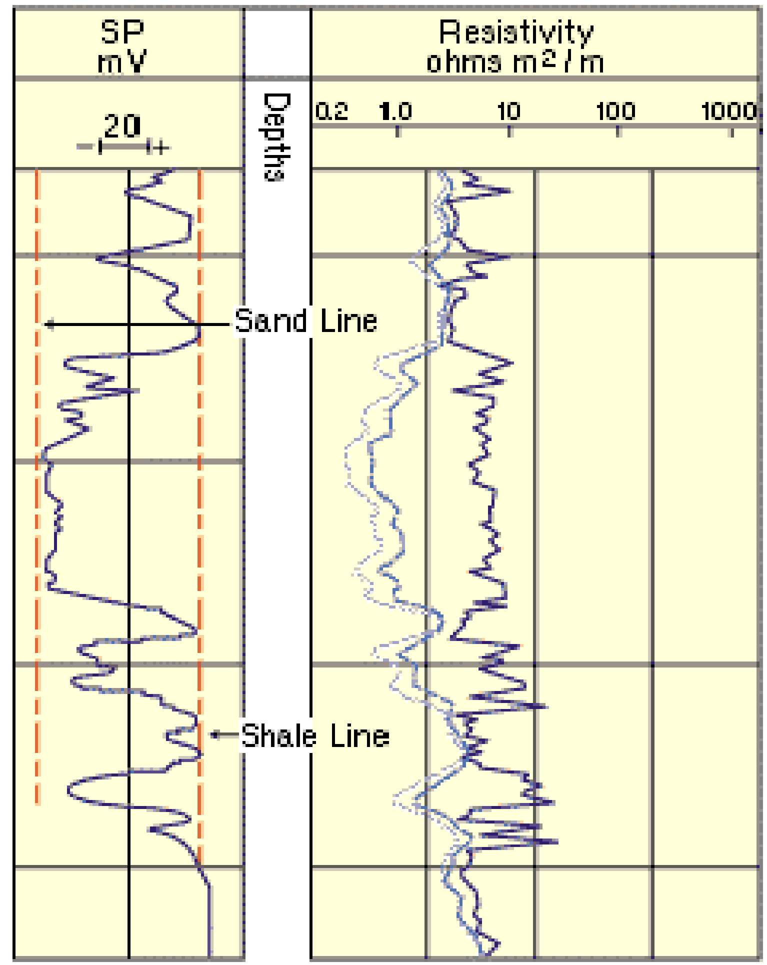
SSP



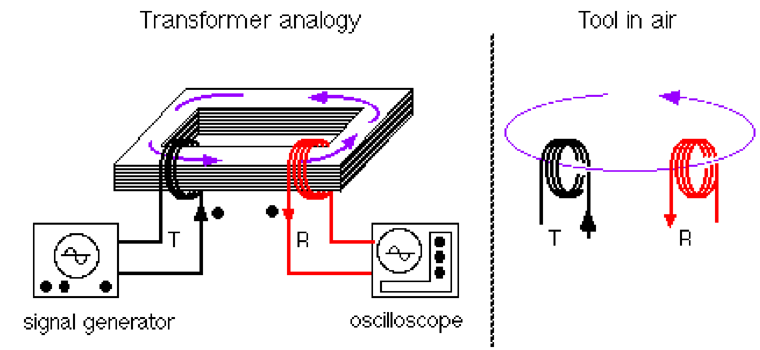
Shaliness indicator

Percentage of Shale

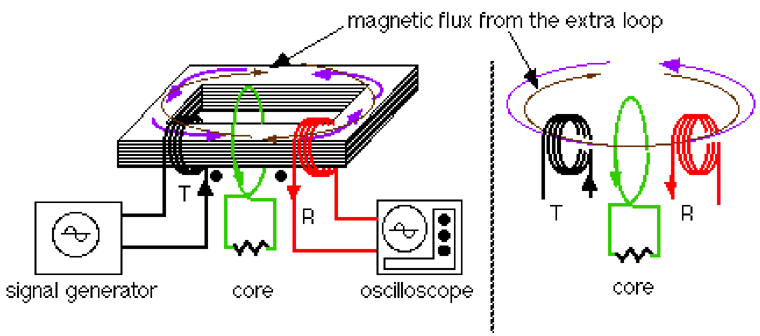
$$\frac{\text{SPlog} - \text{SPsand}}{\text{SPshale} - \text{SPsand}}$$



Induction Theory



The signal generator feeding the transmitter coil will induce a magnetic field in the conductive transformer core. The changing magnetic field in the core will induce voltage in the receiving coil.



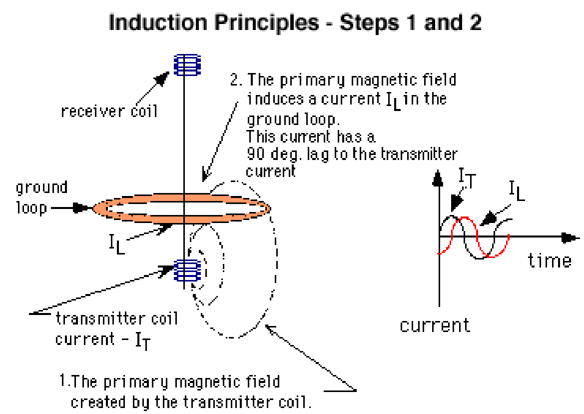


Figure 3-2: Induction Principles - Step 1 and 2.

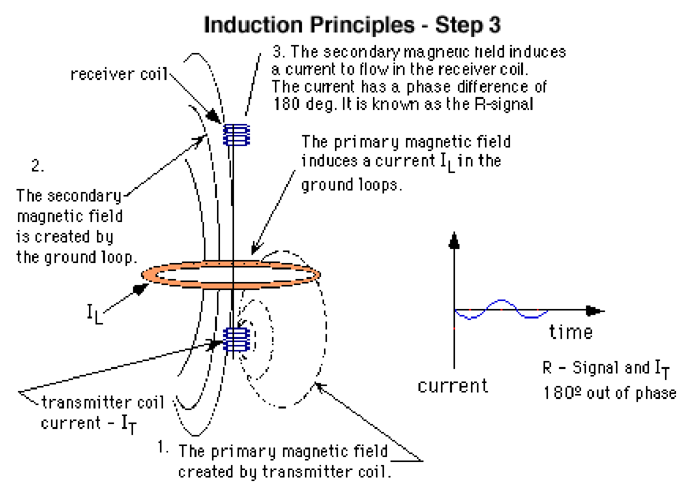
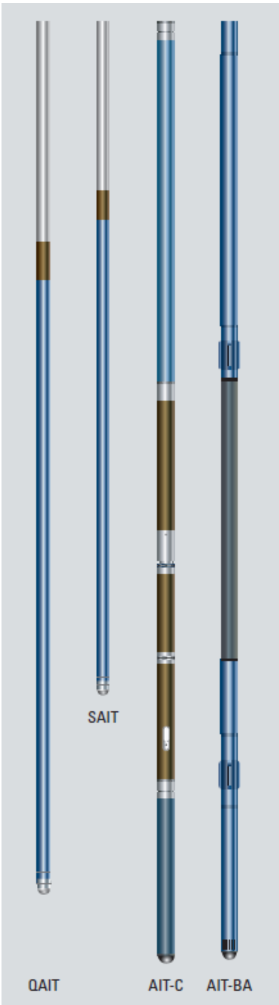


Figure 3-3: Induction Principles - Step 3.

Resistivity Measurements: Induction Logging Tools



Measurement Specifications

	AIT-B and AIT-C	AIT-H and AIT-M	SAIT	HIT
Output	10-, 20-, 30-, 60-, and 90-in [25.40-, 50.80-, 76.20-, 152.40-, and 228.60-cm] deep induction resistivities, SP, R_m			
Logging speed	3,600 ft/h [1,097 m/h]			
Range of measurement	0.1 to 2,000 ohm.m			
Vertical resolution	1, 2, and 4 ft [0.30, 0.61, and 1.22 m]			
Accuracy	Resistivities: ±0.75 us/m (conductivity) or 2% (whichever is greater)			
Depth of investigation†	AO/AT/AF10: 10 in [25.40 cm] AO/AT/AF20: 20 in [50.80 cm] AO/AT/AF30: 30 in [76.20 cm] AO/AT/AF60: 60 in [152.40 cm] AO/AT/AF90: 90 in [228.60 cm]			
Mud type or weight limitations	Salt-saturated muds are usually outside the operating range of induction tools.			
Combinability	Combinable with most services	Platform Express platform	SlimAccess platform	Xtreme platform
Special applications			Slim wellbores Severe doglegs H_2S service	High temperature H_2S service

† AO = 1-ft [0.30-m] vertical resolution, AT = 2-ft [0.61-m] vertical resolution, AF = 4-ft [1.22-m] vertical resolution

Mechanical Specifications

	AIT-B and AIT-C	AIT-H	AIT-M	SAIT	HIT	QAIT
Temperature rating	350 degF [177 degC]	257 degF [125 degC]	302 degF [150 degC]	302 degF [150 degC]	500 degF [260 degC]	500 degF [260 degC]
Pressure rating	20,000 psi [138 MPa]	15,000 psi [103 MPa]	15,000 psi [103 MPa]	14,000 psi [97 MPa]	25,000 psi [172 MPa]	30,000 psi [207 MPa]
Borehole size—min.	4¾ in [12.07 cm]	4¾ in [12.07 cm]	4¾ in [12.07 cm]	4 in [10.16 cm]	4⅞ in [12.38 cm]	3⅞ in [9.84 cm]
Borehole size—max.	20 in [50.80 cm]	20 in [50.80 cm]	20 in [50.80 cm]	9 in [22.86 cm]	20 in [50.80 cm]	20 in [50.80 cm]
Outside diameter	3.875 in [9.84 cm]	3.875 in [9.84 cm]	3.875 in [9.84 cm]	2.75 in [6.99 cm] with 0.25-in [0.64-cm] standoff	3.875 in [9.84 cm]	3 in [7.62 cm]
Length	33.5 ft [10.21 m]†	16 ft [4.88 m]	16 ft [4.88 m]	23.6 ft [7.19 m]†	29.2 ft [8.90 m]†	30.8 ft [9.39 m]†
Weight	575 lbm [261 kg]	255 lbm [116 kg]	282 lbm [128 kg]	238 lbm [108 kg]	625 lbm [283 kg]	499 lbm [226 kg]
Tension	16,500 lbf [73,400 N]	20,000 lbf [88,960 N]	20,000 lbf [88,960 N]	20,000 lbf [88,960 N]	20,000 lbf [88,960 N]	20,000 lbf [88,960 N]
Compression	2,300 lbf [10,230 N]	6,000 lbf[26,690 N]	6,000 lbf[26,690 N]	3,300 lbf [14,680 N]	6,000 lbf [26,690 N]	2,000 lbf [8,900 N]

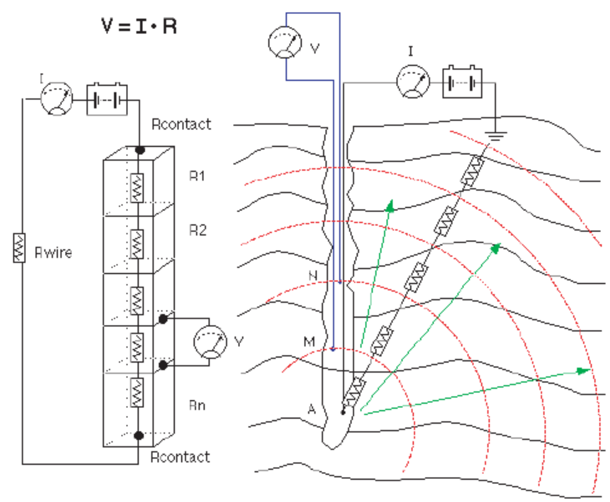
Laterolog Principals

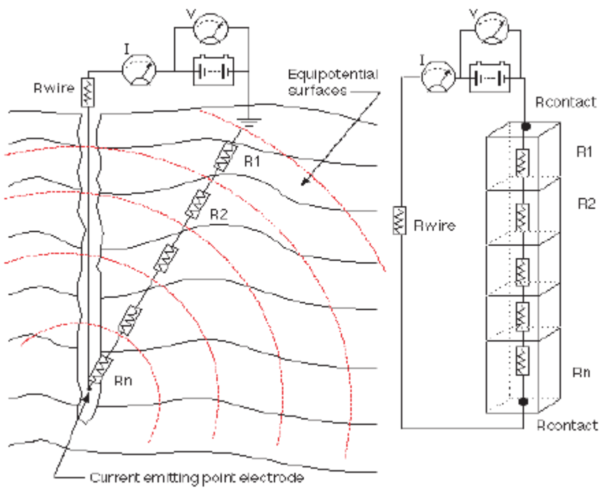
The basic equation for resistivity is

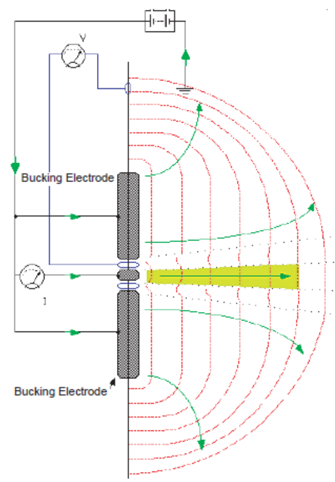
$$R = K \times \frac{V}{I} = K \times r$$

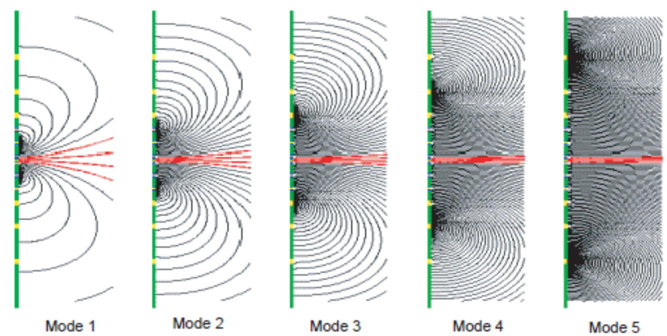
where

Term	Definition
R	= resistivity (Ω.m)
K	= geometrical factor (m)
r	= resistance (Ω)



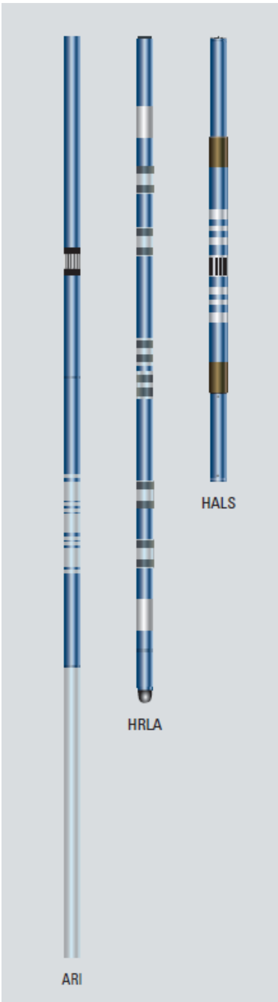






Current distributions for HRLA resistivities RLA1 to RLA5 in homogeneous 1 Ω.m formation

Resistivity Measurements: Laterolog Logging Tools



Measurement Specifications

	ARI Tool	HRLA Tool[†]	HALS
Output	Deep laterolog, shallow laterolog, high-resolution deep laterolog, Gröningen laterolog, azimuthal resistivity, resistivity images	Deep laterolog, shallow laterolog, high-resolution resistivity, diameter of invasion, resistivity images, mud resistivity	High-resolution deep laterolog, high-resolution shallow laterolog, resistivity images, mud resistivity
Logging speed	1,800 ft/h [549 m/h]	3,600 ft/h [1,097 m/h]	3,600 ft/h [1,097 m/h]
Range of measurement	0.2 to 100,000 ohm.m	R_m = 1 ohm.m: 0.2 to 100,000 ohm.m R_m = 0.02 ohm.m: 0.2 to 20,000 ohm.m	0.2 to 40,000 ohm.m
Vertical resolution	Deep and shallow laterolog: 29-in [73.66-cm] beam width High-resolution laterolog: 8-in [20.32-cm] beam width	12 in [30.48 cm]	Standard resolution: 18 in [45.72 cm] in 6-in [15.24-cm] borehole High resolution: 8 in [20.32 cm] in 6-in [15.24-cm] borehole
Accuracy	1 to 2,000 ohm.m: ±5% 2,000 to 5,000 ohm.m: ±10% 5,000 to 100,000 ohm.m: ±20%	1 to 2,000 ohm.m: ±5% 2,000 to 5,000 ohm.m: ±10% 5,000 to 100,000 ohm.m: ±20%	1 to 2,000 ohm.m: ±5%
Depth of investigation	40 in [101.6 cm] (varies with formation and mud resistivities)	50 in [127.0 cm][‡]	32 in [81.3 cm] (varies with formation and mud resistivities)
Mud type or weight limitations	R_m < 5 ohm.m	Conductive mud systems only	Conductive mud systems only
Combinability	Combinable with most tools	Combinable with most tools	Bottom component of Platform Express system

† HRLA performance specifications are for 8-in [20.32-cm] borehole.
‡ Median response at 10:1 contrast of true to invaded zone resistivity

Mechanical Specifications

	ARI Tool	HRLA Tool	HALS
Temperature rating	350 degF [177 degC]	302 degF [150 degC]	257 degF [125 degC]
Pressure rating	20,000 psi [138 MPa]	15,000 psi [103 MPa]	10,000 psi [69 MPa]
Borehole size—min.	4½ in [11.43 cm]	5 in [12.70 cm]	5½ in [13.97 cm]
Borehole size—max.	21 in [53.34 cm]	16 in [40.64 cm]	16 in [40.64 cm]
Outside diameter	3⅝ in [9.21 cm][†] 7¼ in [18.41 cm][†]	3⅝ in [9.21 cm]	3⅝ in [9.21 cm]
Length	33.25 ft [10.13 m]	24.1 ft [7.34 m]	16 ft [4.88 m]
Weight	579 lbm [263 kg]	394 lbm [179 kg]	221 lbm [100 kg]
Tension	3,000 lbf [13,345 N]	30,000 lbf [133,450 N]	20,000 lbf [88,960 N]
Compression	2,000 lbf [8,900 N]	With fin standoff: 3,600 lbf [16,010 N] With rigid centralizers: 7,800 lbf [34,700 N]	2,400 lbf [10,675 N] With four rigid centralizers: 9,400 lbf [41,810 N]

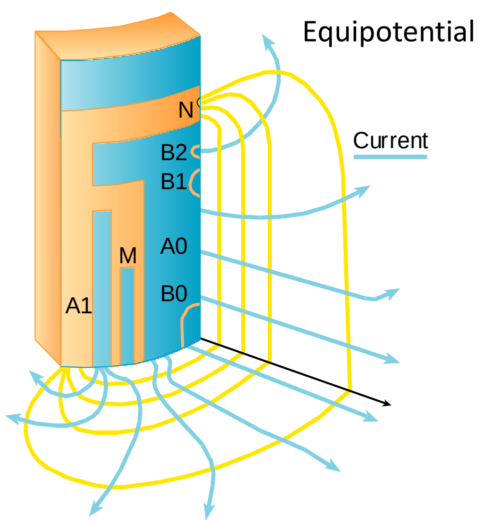
† ARI tool is available in two sizes to fit different borehole sizes.

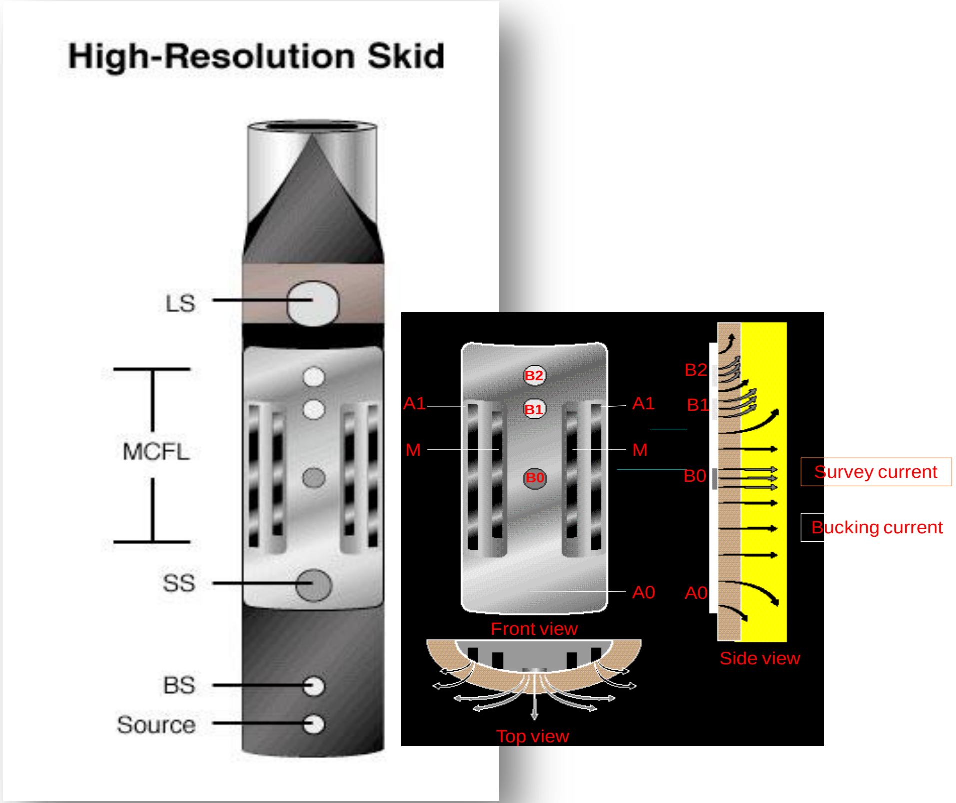
Micro Spherically Focused Measurement

Vertical Resolution	DLIS Outputs
Standard, 18 in. [45.7 cm]	RXOZ, RMCZ, RSOZ
High, 8 in. [20.3cm]	RXO8, RSO8
Enhanced, 2 in. [5.1 cm]	RXOI, RSOI

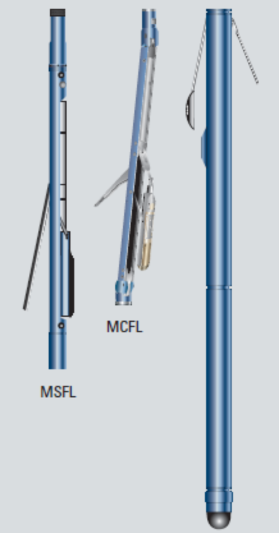
- Cylindrically Focused Measurement

- 3 inch depth of investigation
- Plus HMIN and HMNO Microlog





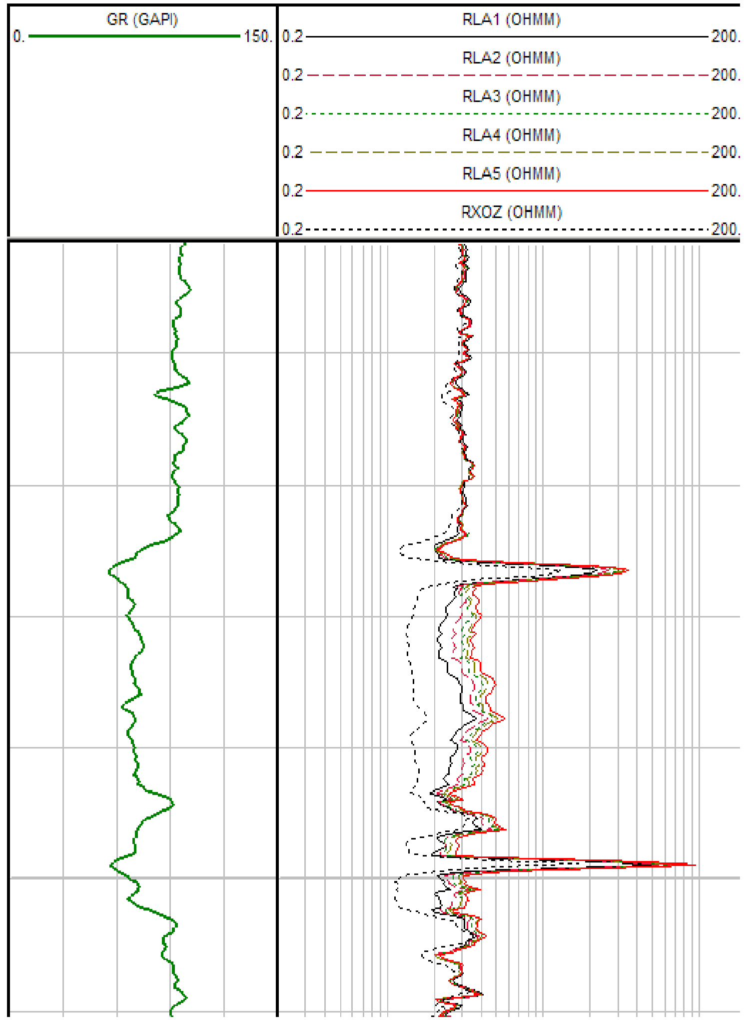
Microresistivity Measurements: Microresistivity Tools



Measurement Specifications			
	MicroSFL Tool	**MCFL**	**PCD with Microlog**
Output	Resistivity of the invaded zone	Resistivity of the invaded zone	Micro-normal, micro-inverse, two calipers (single axis)
Logging speed	1,800 ft/h [549 m/h]	3,600 ft/h [1,097 m/h]	3,600 ft/h [1,097 m/h]
Range of measurement	0.2 to 1,000 ohm.m	0.2 to 2,000 ohm.m	Short arm: 1.25 in [3.18 cm] Hole diameter: 22 in [55.9 cm]
Vertical resolution	2 to 3 in [5.08 to 7.67 cm]	0.70 in [1.78 cm]	Micro-normal: 2 in [5.08 cm] Micro-inverse: 1 in [2.54 cm]
Accuracy	±2 ohm.m	±5%	Caliper: 0.2 in [0.51 cm]
Depth of investigation	0.7 in [1.78 cm]	3.0 in [7.62 cm]	Micro-normal: ~1.5 in [~3.8 cm] Micro-inverse: ~0.5 in [~1.3 cm]
Mud type or weight limitations	Oil-base mud	Oil-base mud	Oil-base mud
Combinability	Combinable with most tools	Housed with the TLD in the High-Resolution Mechanical Sonde of the Platform Express system	Combinable with most tools
Special applications			Provides eccentric positioning for other services that require it

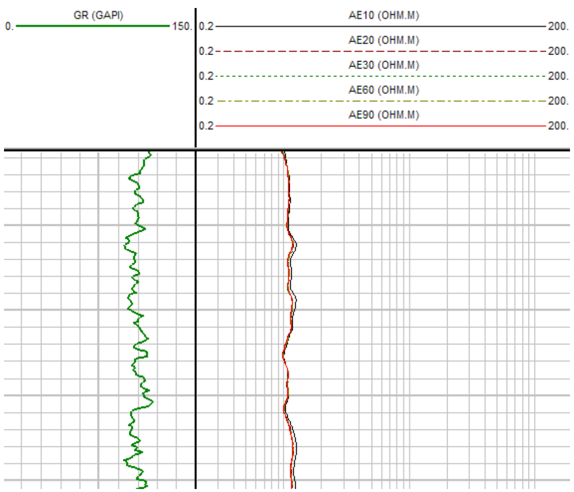
Mechanical Specifications			
	MicroSFL Tool	**MCFL**	**PCD with Microlog**
Temperature rating	350 degF [177 degC]	302 degF [150 degC]	350 degF [177 degC]
Pressure rating	20,000 psi [138 MPa]	15,000 psi [103 MPa]	20,000 psi [138 MPa]
Borehole size—min.	5½ in [13.97 cm]	Without bow spring: 5⅕ in [13.21 cm] With bow spring: 6 in [15.24 cm]	Without microlog pad: 6½ in [16.51 cm] With microlog pad: 7 in [22.23 cm]
Borehole size—max.	17½ in [44.45 cm]	16 in [40.64 cm]	22 in [55.88 cm]
Outside diameter	Caliper closed: 4.77 in [12.11 cm]	4.625 in [11.75 cm]	Without pad: 3.375 in [8.57 cm] With slim pad: 5 in [12.70 cm] With standard pad: 6.25 in [15.87 cm]
Length	12.3 ft [3.75 m]	10.85 ft [3.31 m]	17.25 ft [5.26 m]
Weight	313 lbm [142 kg]	171.7 lbm [78 kg]	345 lbm [156 kg]
Tension	40,000 lbf [177,930 N]	50,000 lbf [222,410 N]	40,000 lbf [177,930 N]
Compression	5,000 lbf [22,240 N]	8800 lbf [39,140 N]	5,000 lbf [22,240 N]

Resistivity Log Example

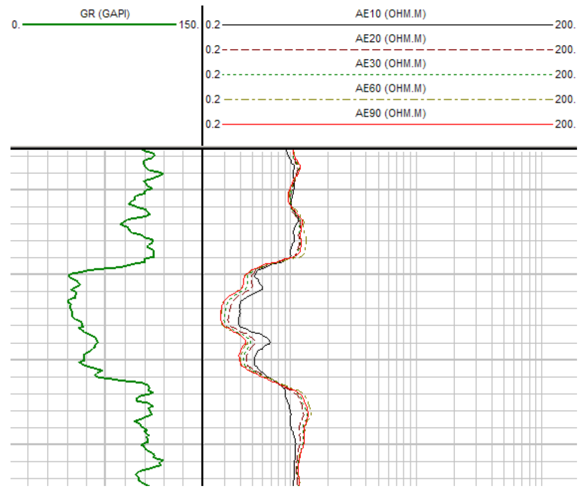


Resistivity Logs

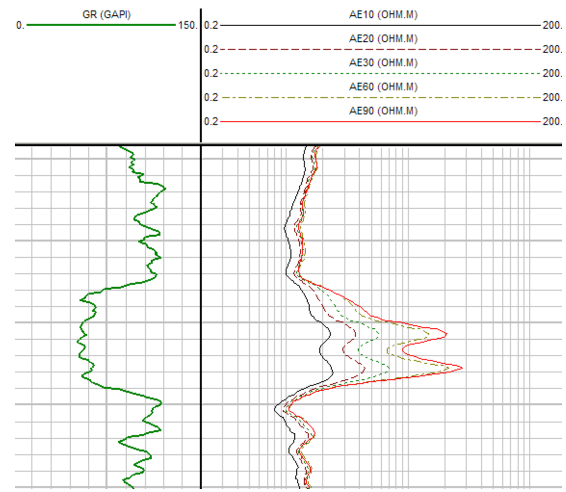
SHALE RESPONSE



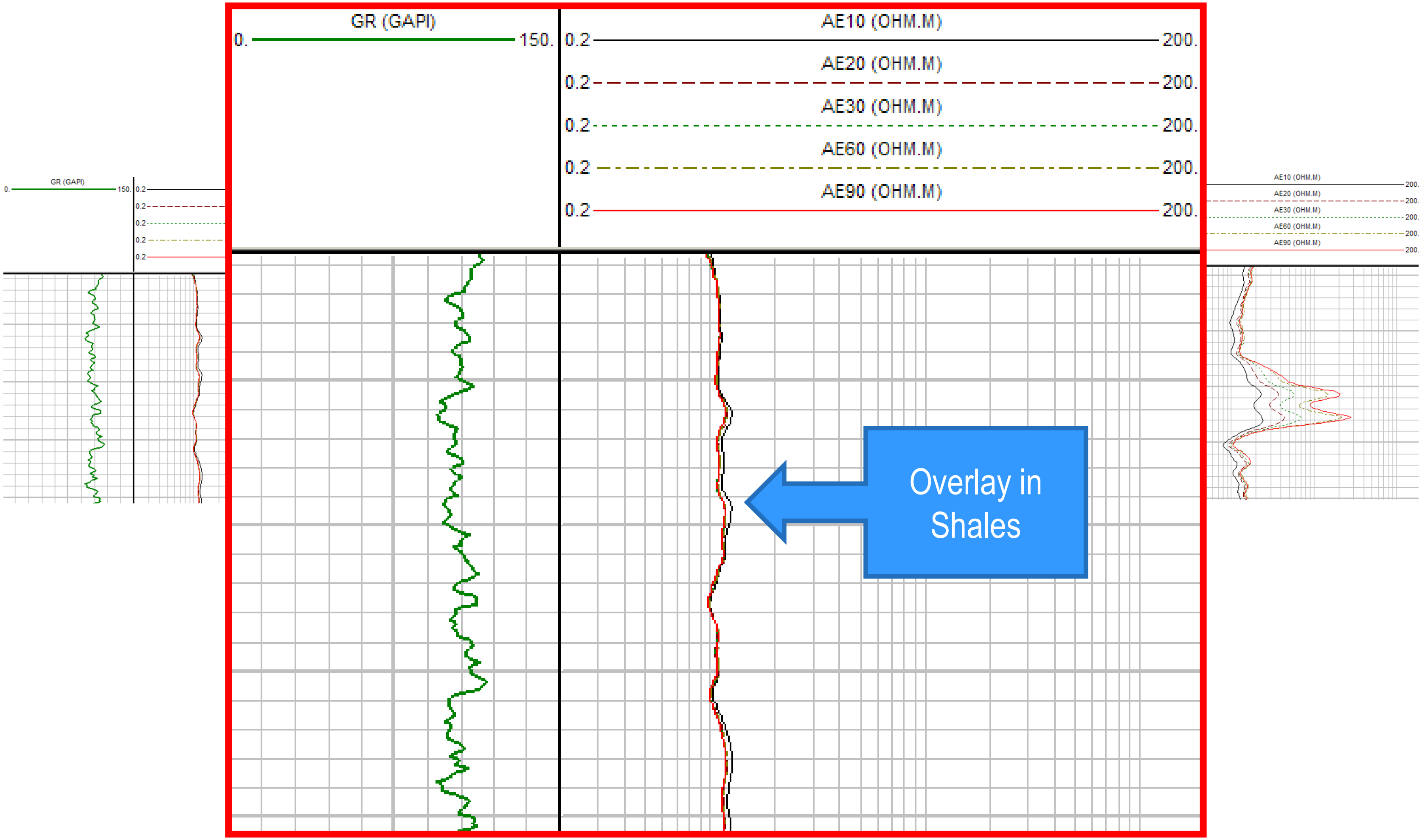
WET RESPONSE



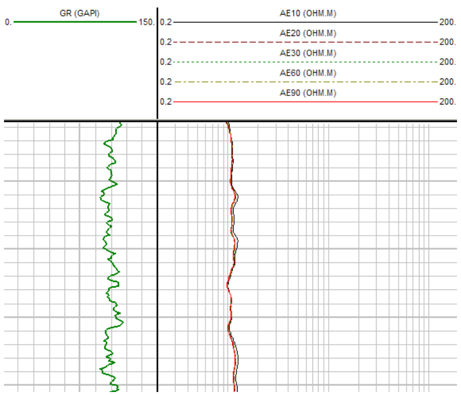
HYDROCARBON RESPONSE

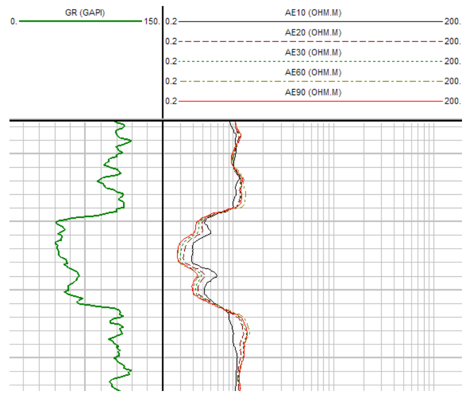


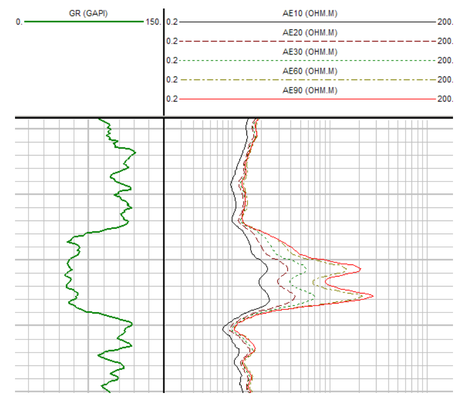
Resistivity Logs



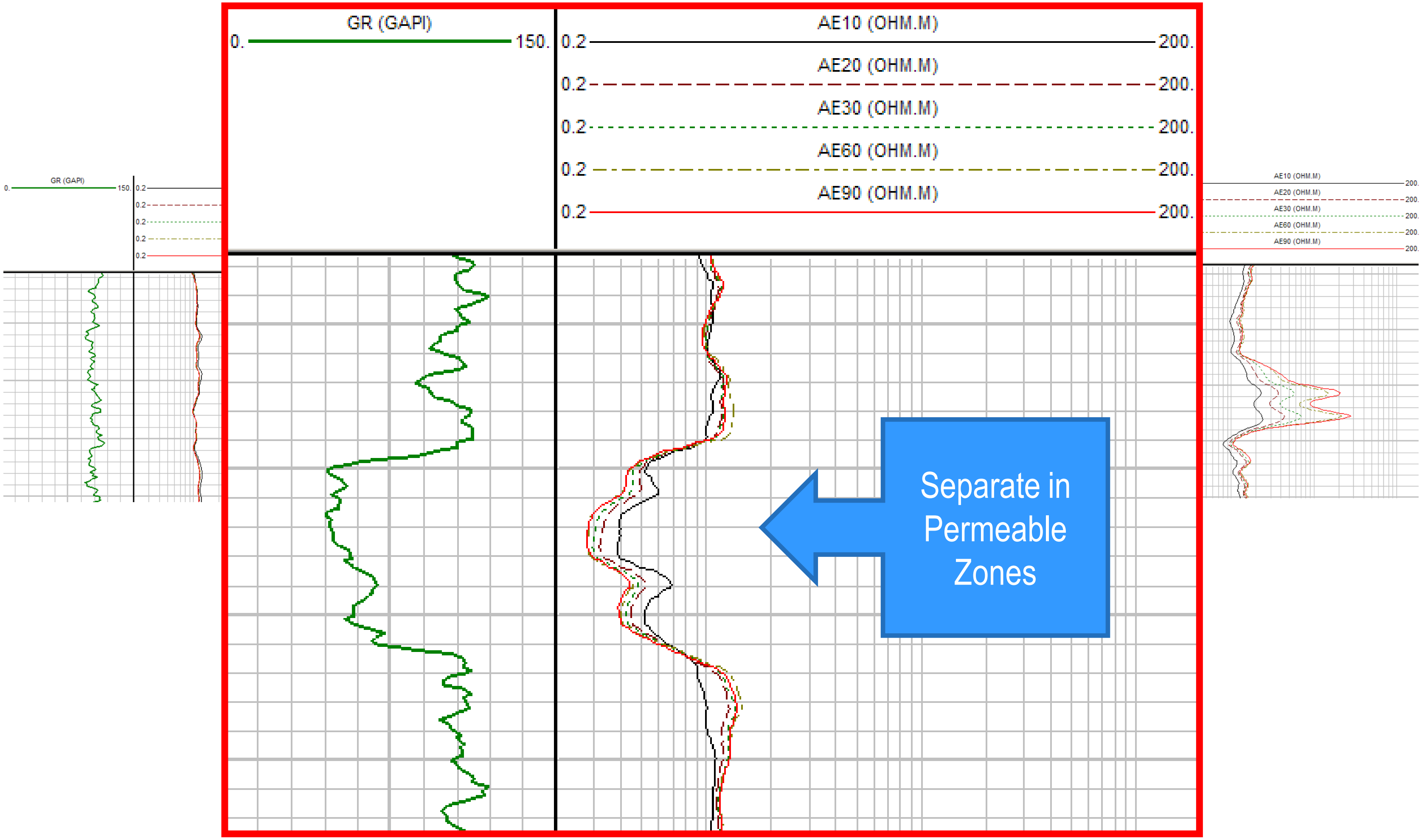
Resistivity Logs



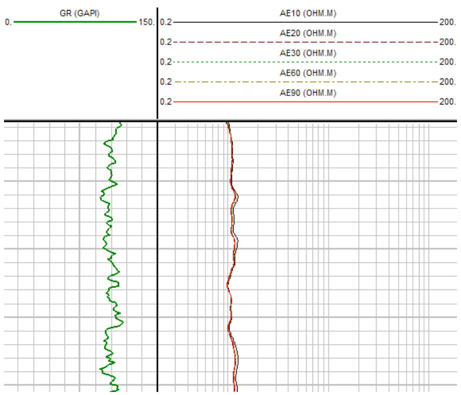


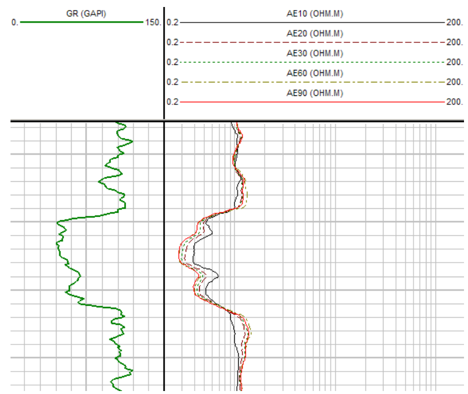


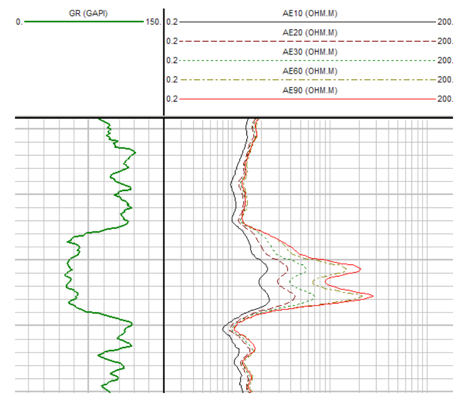
Resistivity Logs



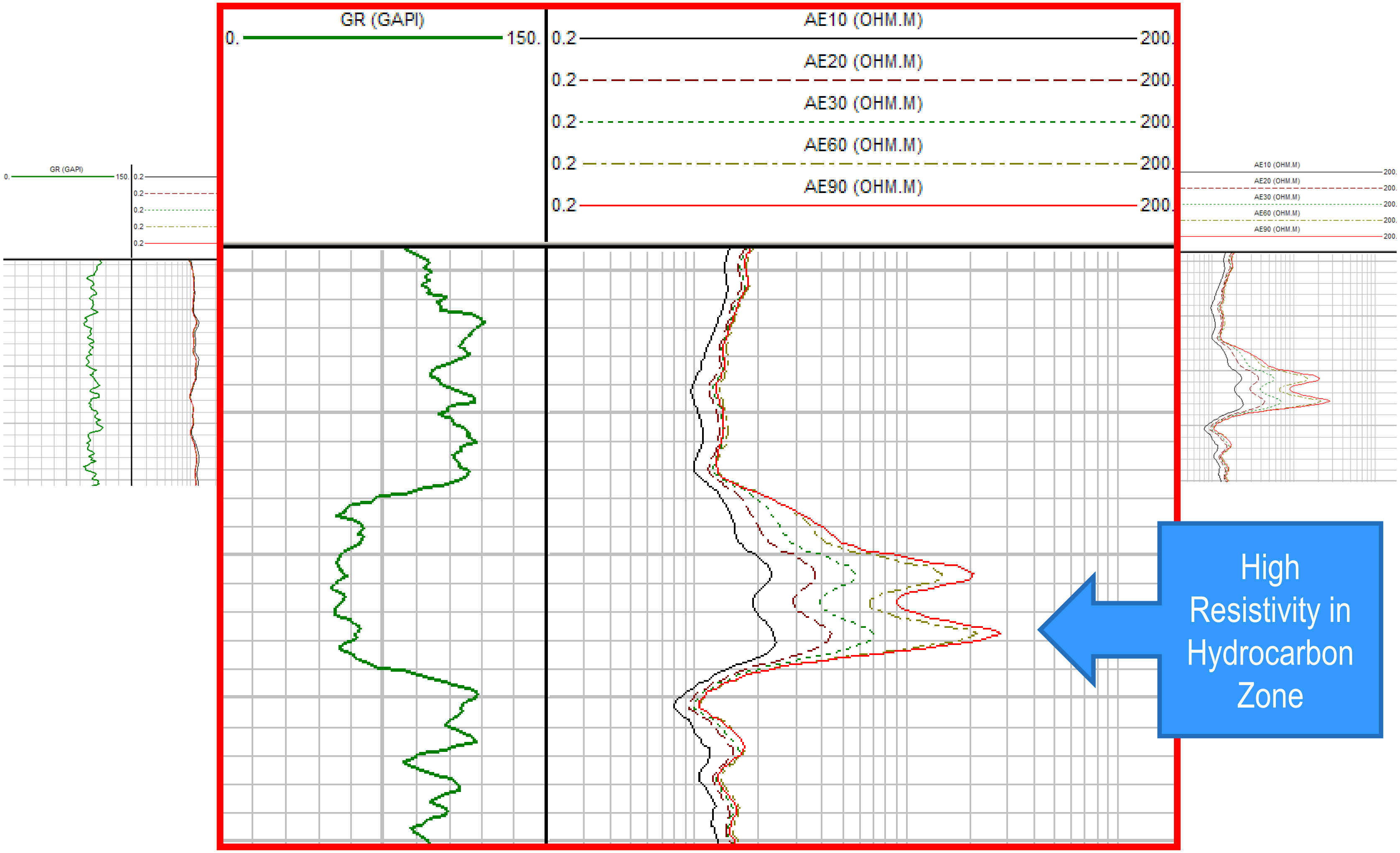
Resistivity Logs



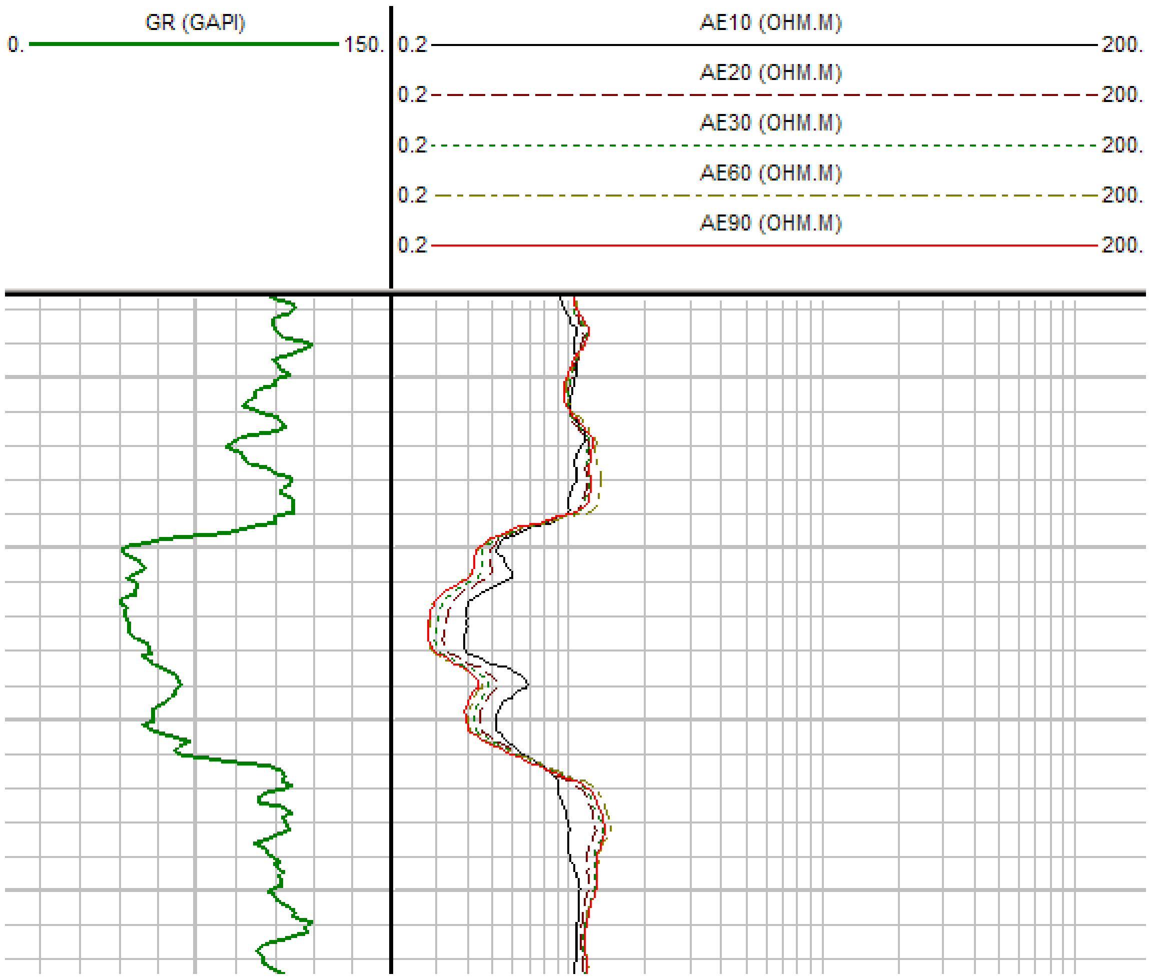




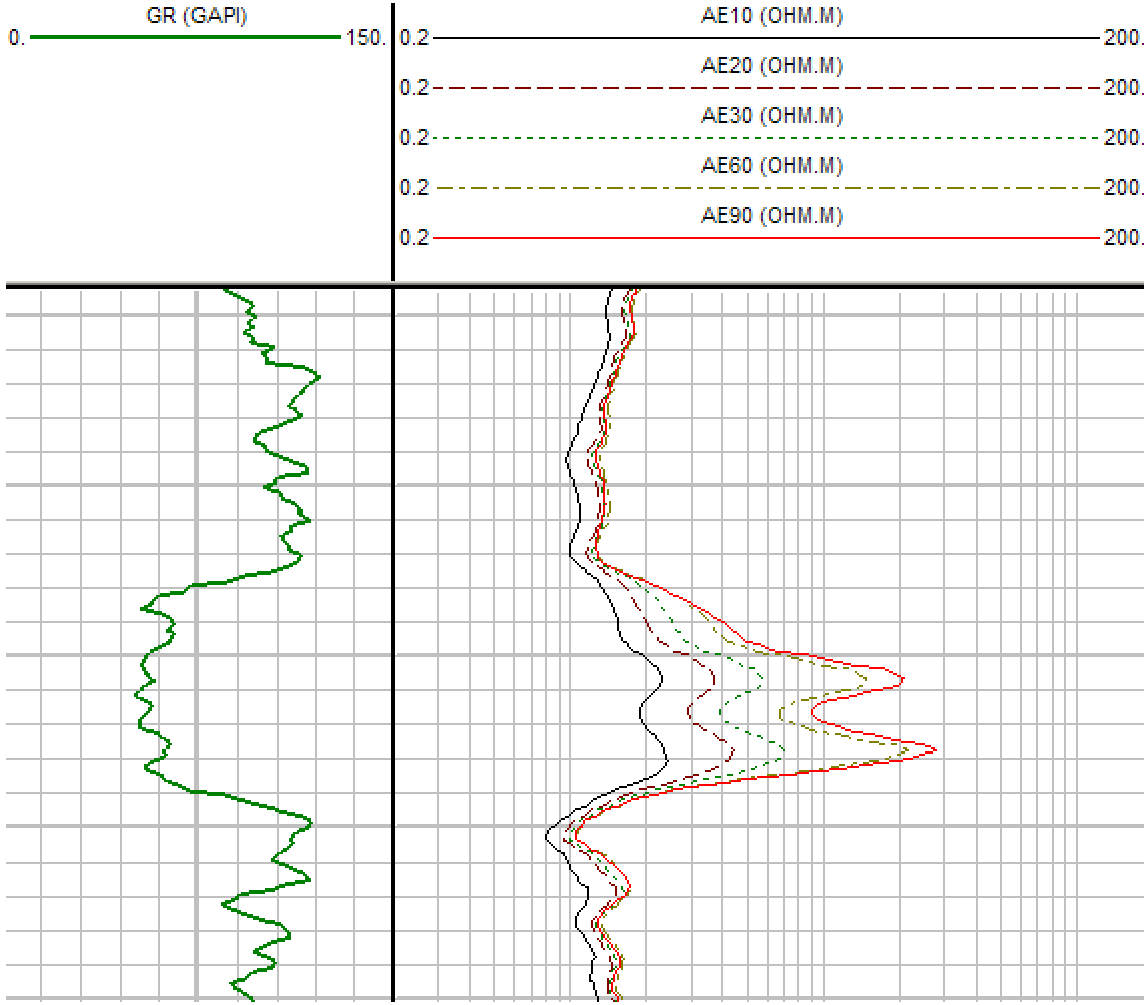
Resistivity Logs



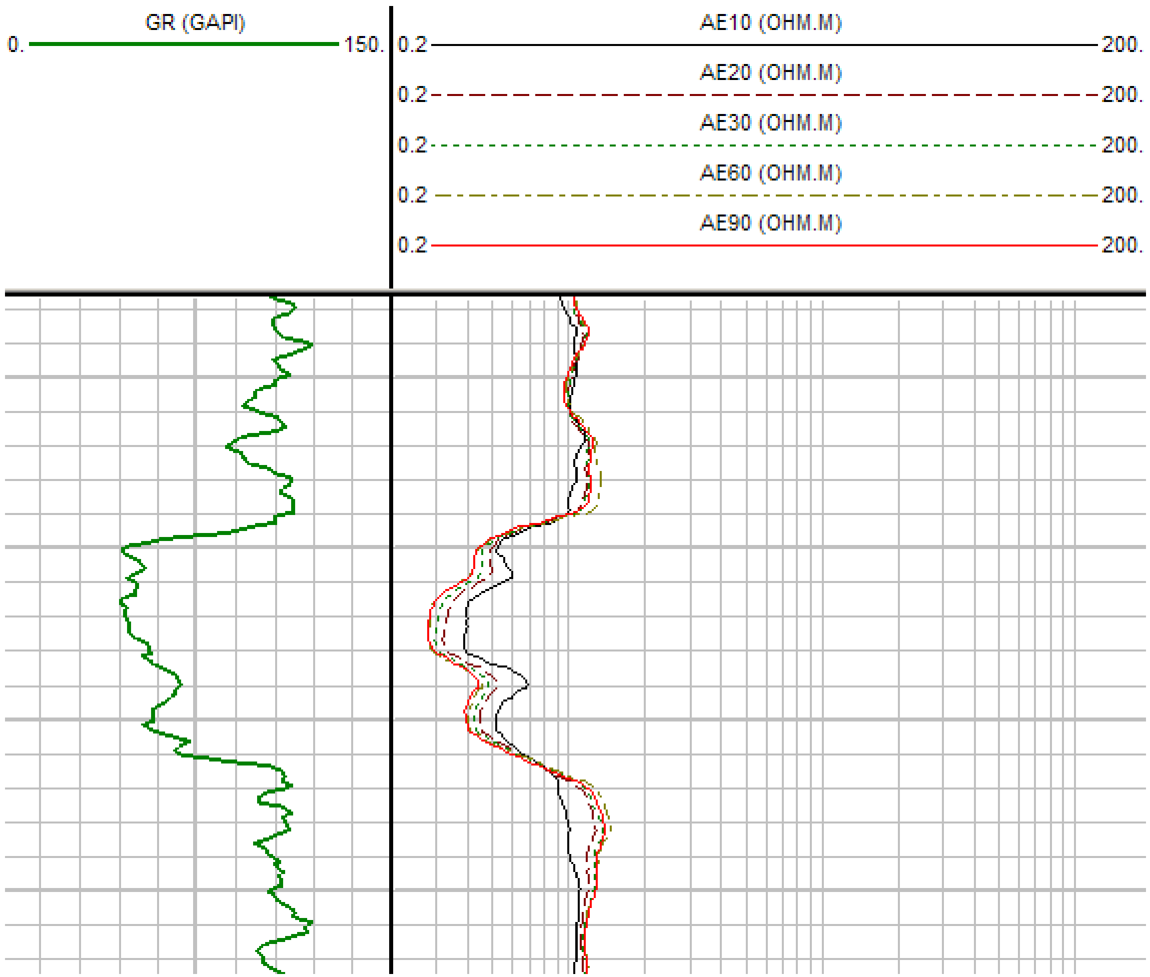
Resistivity Logging –Water-Filled Sand



Resistivity Logging –Hydrocarbon Zone



Resistivity Logging
Induction in a Water-Filled Sand



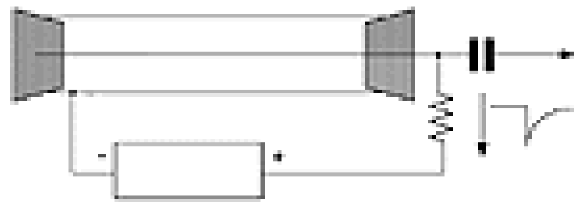
Radiation Detectors

- Two-Step Process
  - Gamma rays interact with detector material
    - γ-rays transfer energy to electron(s) via Photoelectric, Compton or Pair-production
    - Material chosen for high probability of absorption
  - Electron converted to observable signal*
    - Direct electrical signal with gaseous or solid-state detector
    - Conversion (to light): Scintillator/photomultiplier most common

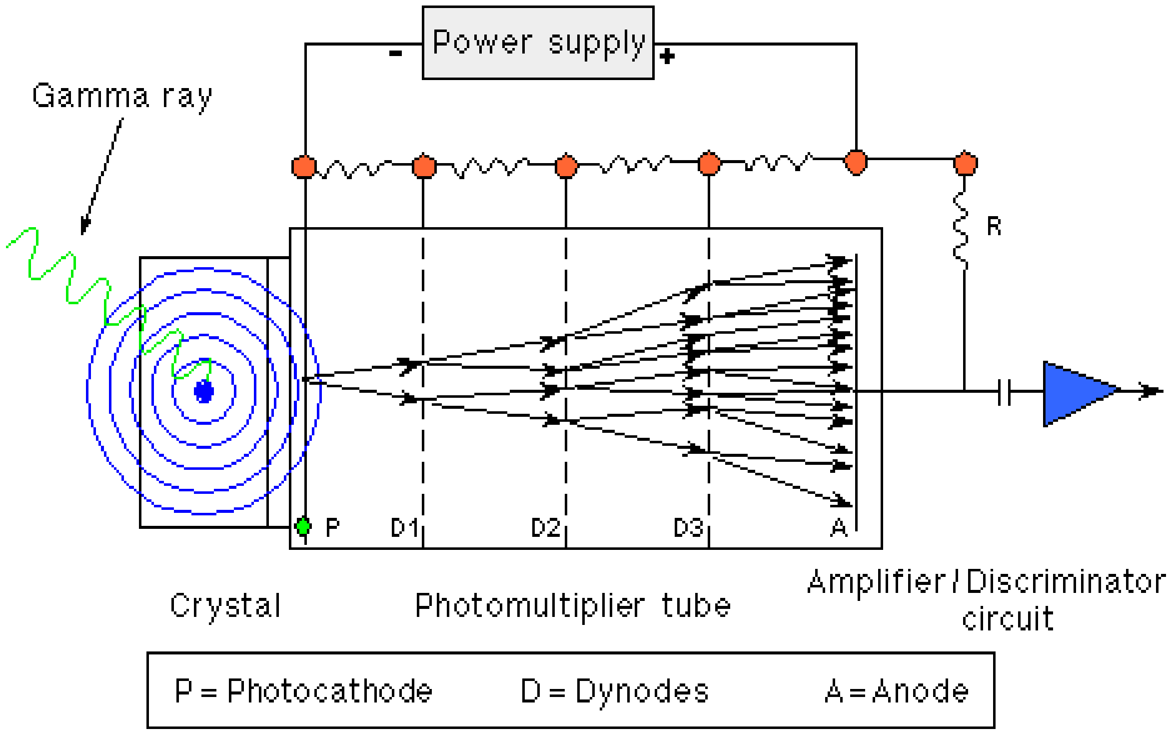
* For gross counting or SPECTROSCOPY

Detectors

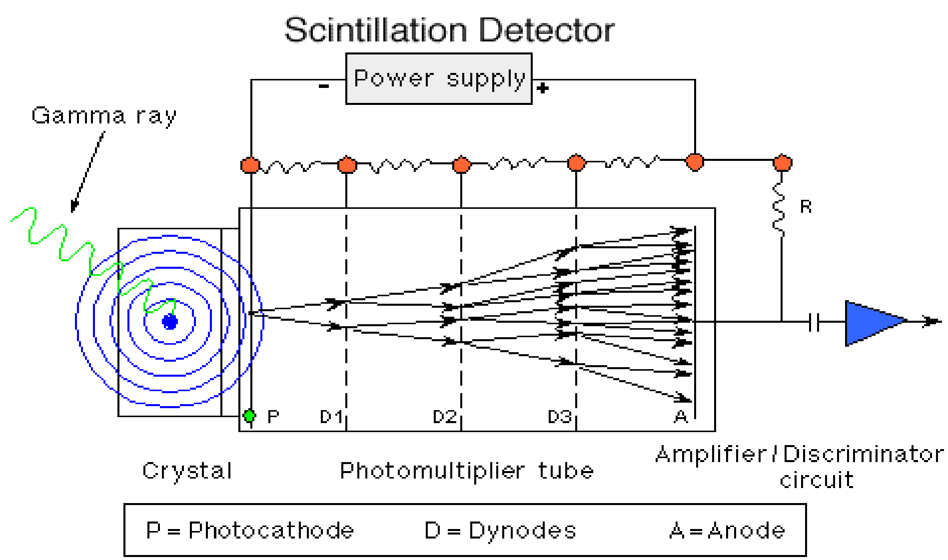
Geiger-Muller Detector

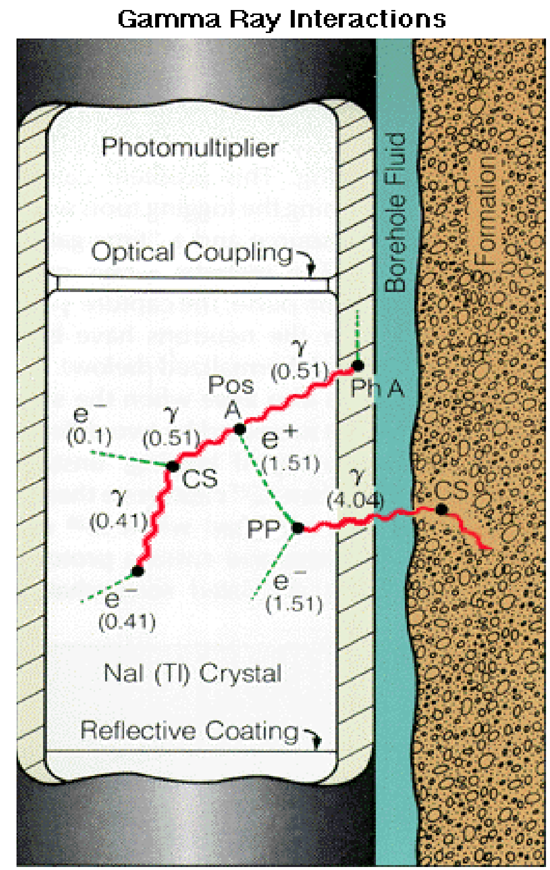


Scintillation Detector



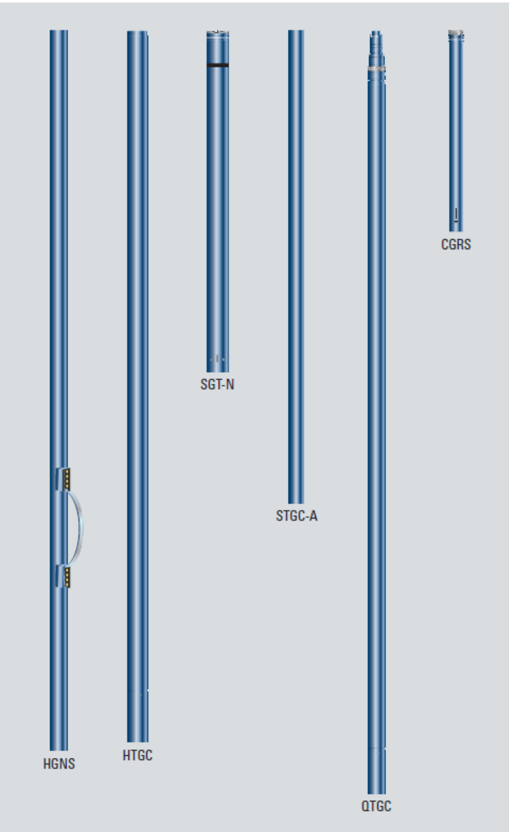
γ-Ray Detection Process





NaI (Thallium-activated sodium iodide) crystal converts energy from gamma ray to light
by PE effect. (energy < than 200 Kev)
This light ejects electrons from photo-cathode of PM tube
These electrons are multiplied in the dynodes, producing a negative pulse at anode
proportional to energy of gamma ray

Nuclear Measurements:
Gamma Ray Tools



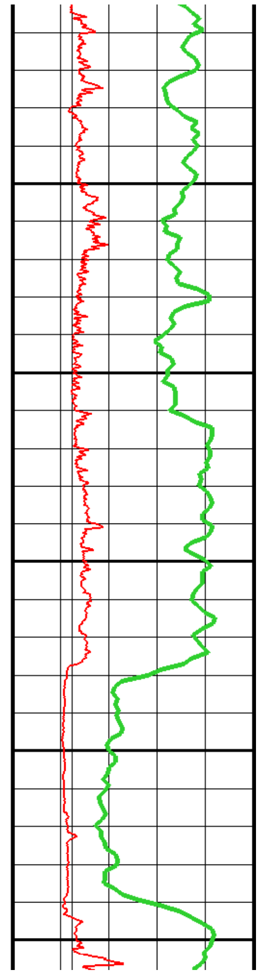
Measurement Specifications

	Highly Integrated Gamma Neutron Sonde (HGNS)	Hostile Environment Telemetry and Gamma Ray Cartridge (HTGC)	Scintillation Gamma Ray Tool (SGT)	Slim Telemetry and Gamma Ray Cartridge (STGC)	SlimXtreme Telemetry and Gamma Ray Cartridge (QTGC)	Combinable Gamma Ray Sonde (CGRS)
Output	Formation gamma ray	Formation gamma ray	Formation gamma ray	Formation gamma ray	Formation gamma ray	Gamma ray activity
Logging speed	3,600 ft/h [1,097 m/h]	1,800 ft/h [549 m/h]	3,600 ft/h [1,097 m/h]	1,800 ft/h [549 m/h]	1,800 ft/h [549 m/h]	Up to 3,600 ft/h [1,097 m/h]
Range of measurement	0 to 1,000 gAPI	0 to 2,000 gAPI	0 to 2,000 gAPI	0 to 2,000 gAPI	0 to 2,000 gAPI	0 to 2,000 gAPI
Vertical resolution	12 in [30.48 cm]	12 in [30.48 cm]	12 in [30.48 cm]	12 in [30.48 cm]	12 in [30.48 cm]	12 in [30.48 cm]
Accuracy	±5%	±5%	±5%	±5%	±5%	±5%
Depth of investigation	24 in [60.96 cm]	24 in [60.96 cm]	24 in [60.96 cm]	24 in [60.96 cm]	24 in [60.96 cm]	24 in [60.96 cm]
Mud type or weight limitations	None	None	None	None	None	None
Combinability	Part of Platform Express system	Combinable with most tools	Combinable with most tools	Combinable with most tools	Combinable with most tools	Combinable with CPLT tool, RSTPro tool
Special applications						H_2S service

Mechanical Specifications

	HGNS	HTGC	SGT	STGC	QTGC	CGRS
Temperature rating	302 degF [150 degC]	500 degF [260 degC]	350 degF [177 degC]	302 degF [150 degC]	500 degF [260 degC]	350 degF [177 degC]
Pressure rating	15,000 psi [103 MPa]	25,000 psi [172 MPa]	20,000 psi [138 MPa]	14,000 psi [97 MPa]	30,000 psi [207 MPa]	20,000 psi [138 MPa]
Borehole size—min.	4½ in [11.43 cm]	4¾ in [12.07 cm]	4⅞ in [12.38 cm]	3½ in [8.89 cm]	3⅞ in [9.84 cm]	1 13/16-in [4.61-cm] seating nipple
Borehole size—max.	No limit for gamma ray measurement	No limit	No limit	No limit	No limit	No limit
Outside diameter	3.375 in [8.57 cm]	3.75 in [9.53 cm]	3.375 in [8.57 cm]	2.5 in [6.35 cm]	3.0 in [7.62 cm]	1 11/16 in [4.29 cm]
Length	10.85 ft [3.31 m]	10.7 ft [3.26 m]	5.5 ft [1.68 m]	7.64 ft [2.33 m]	10.67 ft [3.25 m]	3.2 ft [0.97 m]
Weight	171.7 lbm [78 kg]	265 lbm [120 kg]	83 lbm [38 kg]	71 lbm [32 kg]	180 lbm [82 kg]	16 lbm [7 kg]
Tension	50,000 lbf [222,410 N]	50,000 lbf [222,410 N]	50,000 lbf [222,410 N]	50,000 lbf [222,410 N]	50,000 lbf [222,410 N]	10,000 lbf [44,480 N]
Compression	37,000 lbf [164,580 N]	20,000 lbf [88,960 N]	23,000 lbf [103,210 N]	17,000 lbf [75,620 N]	20,000 lbf [88,960 N]	1,000 lbf [4,450 N]

Gamma Ray Log Example



Neutron Theory

Elastic Neutron Scattering

•Neutron it interacts with a nucleus, but both particles reappear after the interaction.

•Nucleus is excited

•Neutron Loses Energy

slowing down interaction

billiard-ball collision between a fast-moving neutron and a stationary nucleus

Neutrons lose the most energy when they interact elastically with hydrogen (H) nuclei (a proton).

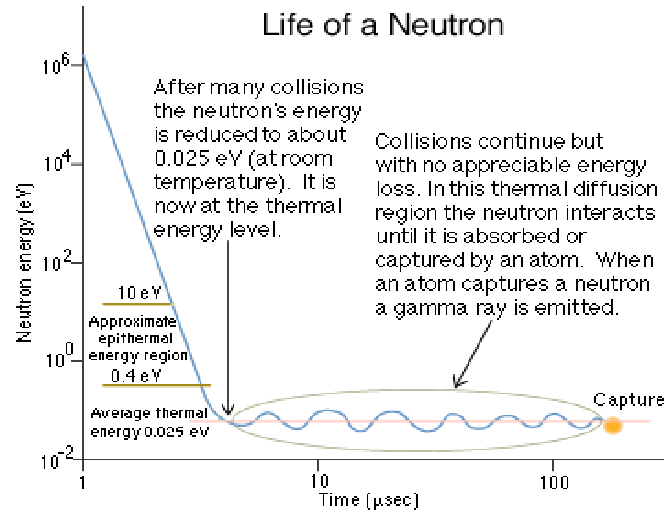
This occurs because the hydrogen nucleus has a mass equal to that of the neutron. Consequently, how efficiently a formation slows down neutrons indicates the abundance of hydrogen, an element present primarily in formation fluids and therefore indicative of porosity.

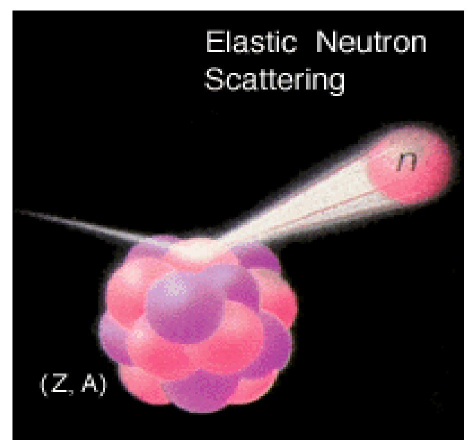
Principal employed by neutron tools;

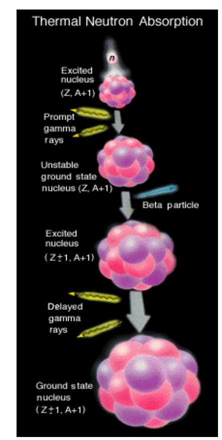
• compensated neutron tool (CNT),

•(HGNS) of the Platform Express,

•accelerator porosity sonde (APS)

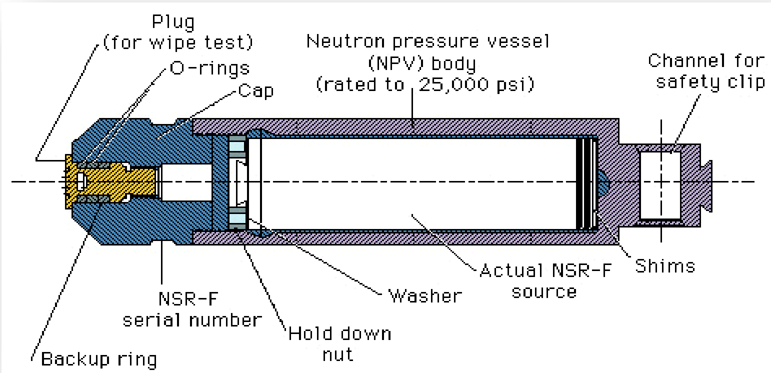






Source and Detector

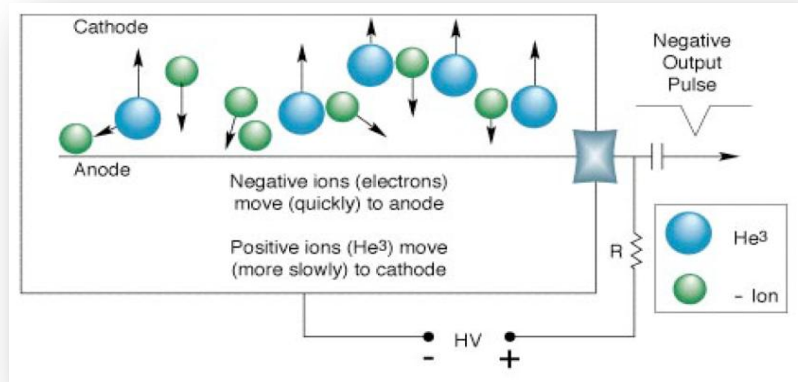
Chemical Source

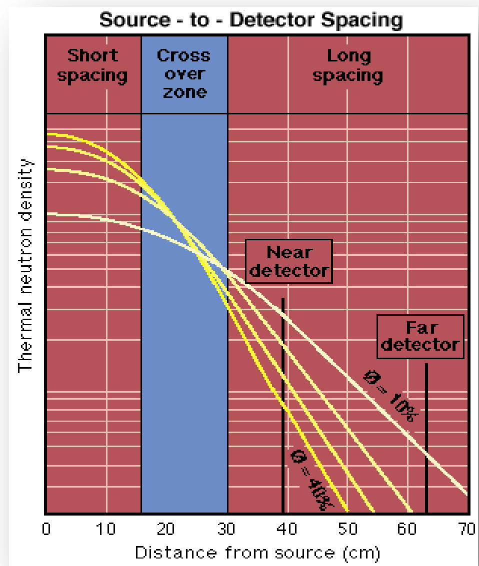


NSR-F Source

Material	americium 241 - beryllium (encapsulated in ceramic microspheres)
Strength	16 Curie
Half-life	458 years
Energy emission level	4.5 MeV average
Generation rate	4 x 10^7 neutrons / second

He+3Detector

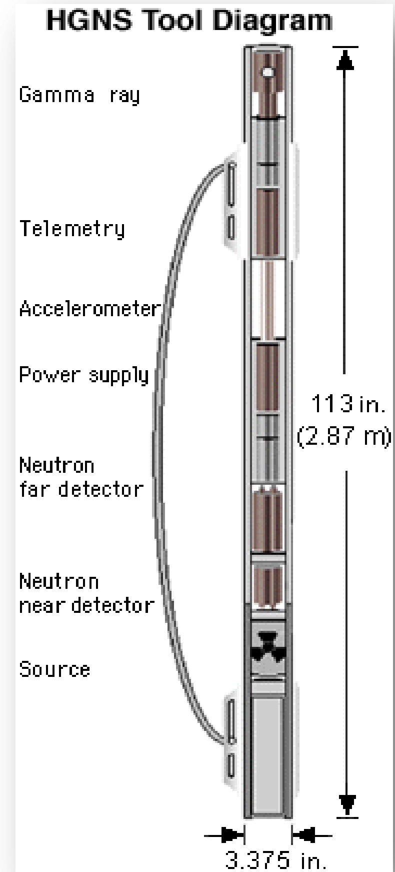




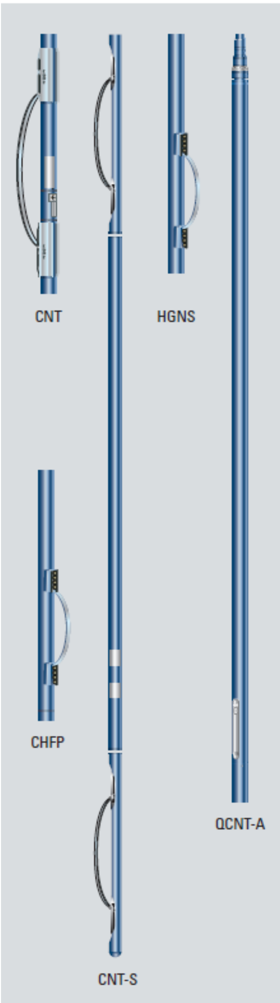
HGNS

Vertical Resolution	DLIS Output
Standard (12 - 24 in)	NPHI,TNPH, NPOR, GR,ECGR
High (8 - 12 in)	HTNP, HNPO,EHGR

- Z-Axis Accelerometer
- Deviation
- Speed Correction
- Tool Telemetry



Neutron Porosity Measurements



Measurement Specifications

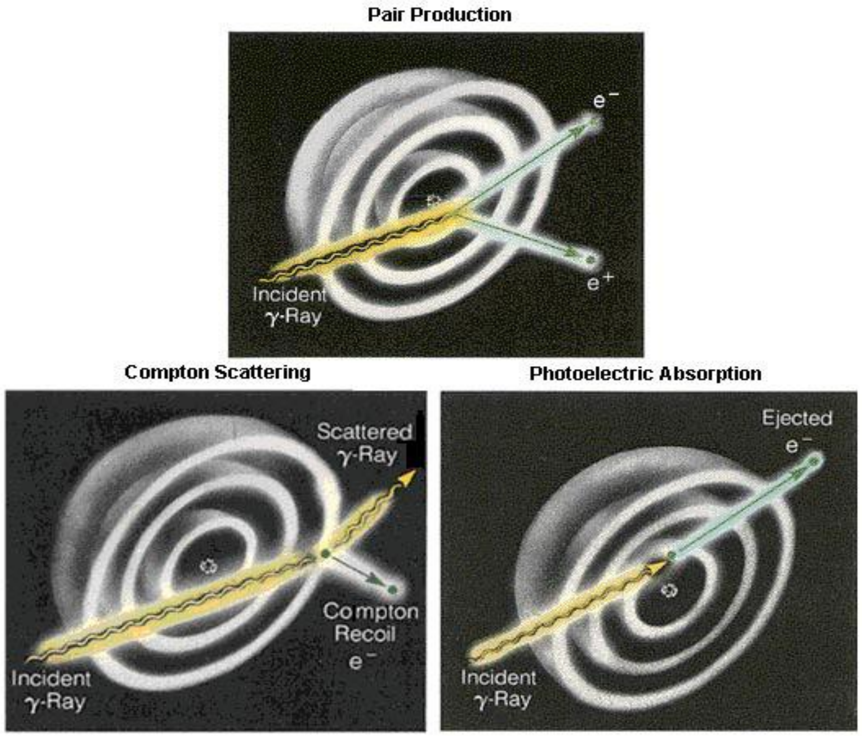
	CNT	CNT-S	HGNS	QCNT
Output	Thermal neutron porosity (uncorrected, environmentally corrected, or alpha processed) CNT-G: Epithermal neutron porosity	Thermal neutron porosity (uncorrected, environmentally corrected, or alpha processed)	Thermal neutron porosity (uncorrected, environmentally corrected, or alpha processed), formation gamma ray, tool acceleration	Thermal neutron porosity (uncorrected, environmentally corrected, or alpha processed)
Logging speed	Standard: 1,800 ft/h [549 m/h] High resolution: 900 ft/h [247 m/h]	Full-resolution max: 1,800 ft/h [549 m/h]	3,600 ft/h [1,097 m/h]	1,800 ft/h [549 m/h]
Range of measurement	0 to 60 pu [0 to 60% uncorrected porosity]			
Vertical resolution	12 in [30.48 cm]	12 in [30.48 cm]	12 in [30.48 cm]	12 in [30.48 cm]
Accuracy	0 to 20 pu: ±1 pu 30 pu: ±2 pu 45 pu: ±6 pu	0 to 20 pu: ±1 pu 30 pu: ±2 pu 45 pu: ±6 pu	0 to 20 pu: ±1 pu 30 pu: ±2 pu 45 pu: ±6 pu	0 to 20 pu: ±1 pu 30 pu: ±2 pu 45 pu: ±6 pu
Depth of investigation	~ 9 in [~23 cm] (varies with hydrogen index of formation)			
Mud type or weight limitations	Thermal measurements not possible in air- or gas-filled wellbores			
Combinability	Combinable with most tools	Combinable with most tools	Part of Platform Express system	Combinable with most tools
Special applications		Slim wellbores Short-radius wells Tubing-conveyed logging On tractor		Slim wellbores Short-radius wells Tubing-conveyed logging On tractor

† Depends on casing and cement thickness, with deployment in casing thickness from 0.205 to 0.545 in [5.21 to 13.84 mm] and correction for combined cement and casing thickness up to 1.5 in [3.8 cm]

Mechanical Specifications

	CNT	CNT-S	HGNS	QCNT
Temperature rating	400 degF [204 degC]	302 degF [150 degC]	302 degF [150 degC]	500 degF [260 degC]
Pressure rating	20,000 psi [138 MPa]	14,000 psi [97 MPa]	15,000 psi [103 MPa]	30,000 psi [207 MPa]
Borehole size—min.	4½ in [12.07 cm]	3¾ in [9.53 cm]	4½ in [11.43 cm]	4 in [10.16 cm]
Borehole size—max.	20 in [50.80 cm]	12 in [30.48 cm]	16 in [40.64 cm]	12 in [30.48 cm]
Outside diameter	Without bow spring eccentralizer: 3.375 in [8.57 cm]	2.75 in [6.99 cm]	3.375 in [8.57 cm]	3 in [7.62 cm]
Length	7.25 ft [2.21 m]	18.4 ft [5.61 m]	10.85 ft [3.31 m]	11.9 ft [3.63 m]
Weight	120 lbm [54 kg]	254 lbm [115 kg]	171.7 lbm [78 kg]	191 lbm [87 kgm]
Tension	50,000 lbf [222,410 N]	68,000 lbf [302,480 N]	50,000 lbf [222,410 N]	50,000 lbf [222,410 N]
Compression	23,000 lbf [102,310 N]	9,600 lbf [42,700 N]	37,000 lbf [164,580 N]	15,000 lbf [66,720 N]

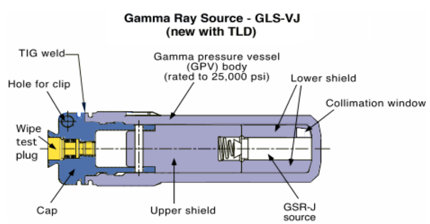
PEX Density Principals of Measurement



Pair Production:
The conversion of a gamma ray into an electron and positron when the gamma ray enters the strong electric field near an atom's nucleus is called pair production.
•GR Energies > 10 MeV.
•Follows $e=mc^2$

Compton Scattering
•GR Sources are selected to generate GRs in this range
•This phenomenon, discovered in 1923 by the American physicist Arthur Holly Compton,
•scattering of a gamma ray by an orbital electron.
• As a result of this interaction, the gamma ray loses energy and an electron is ejected from its orbit.
•Compton scattering predominates in the 75 keV to 10 MeV energy range.

Photoelectric Absorption
•The disappearance of a low-energy gamma ray as it collides with an atom, causing the ejection of an orbital electron
•energies below 100 keV
•predominates at energies below 75 keV.

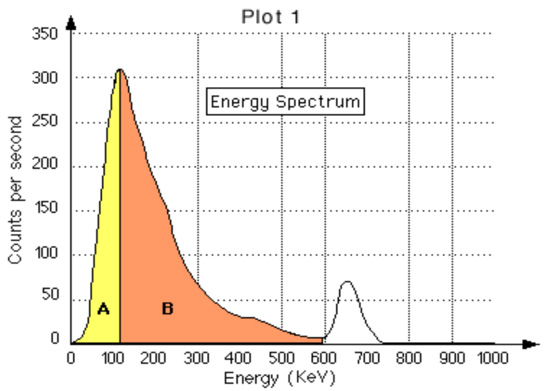


GSR-J Source

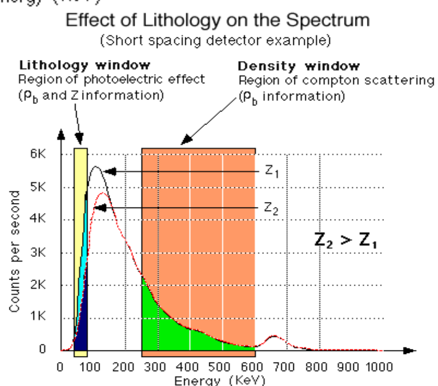
Material	Cesium 137 (encapsulated in ceramic microspheres)
Strength	1.7 Curie
Half life	30.2 years
Energy emission level	662 keV

THRACE BASIN
NATURAL GAS TÜRKİYE CORPORATION

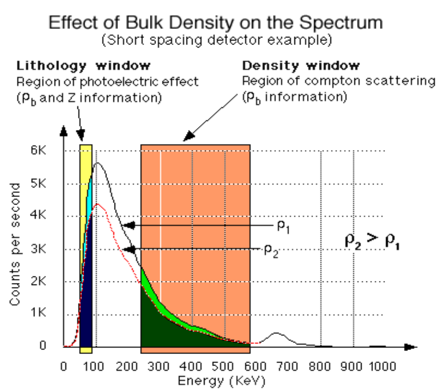
Density Energy Spectrum



- Recorded Energy Spectrum



- Effect of Lithology

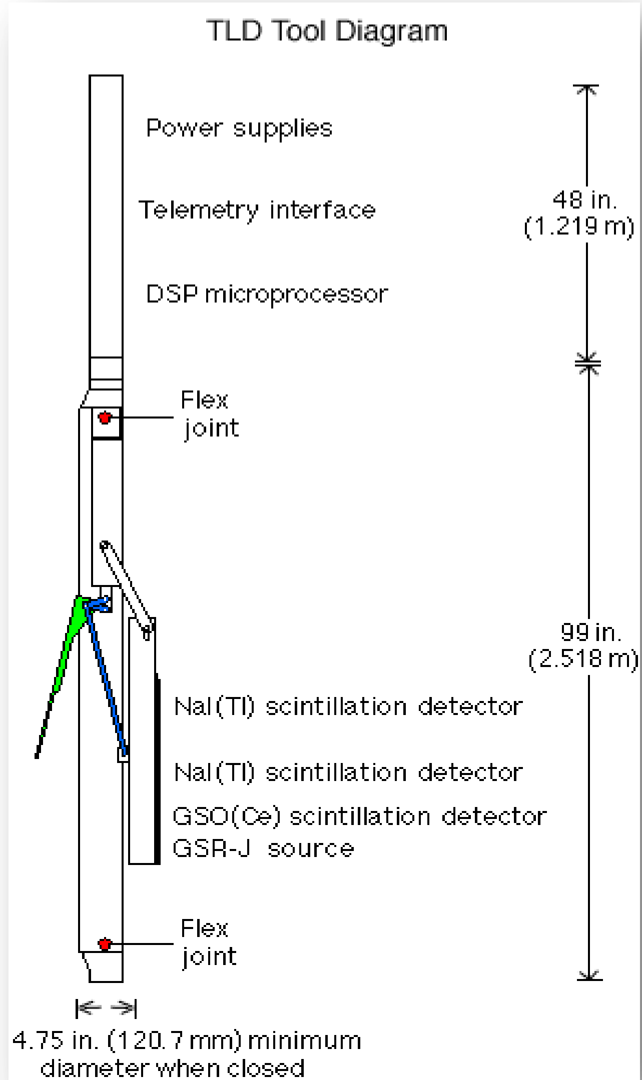


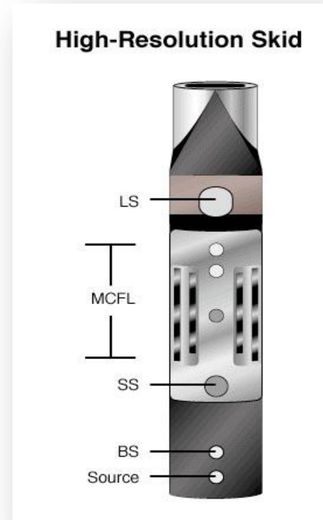
Effect of Density

PEX Density Measurement

Estimates	Outputs
Standard resolution	RHOZ, PEFZ, UZ, DSOZ, ROMZ, PEMZ
High resolution	RHO8, PEF8, U8, DSO8, ROM8, PEM8
Enhanced	RHOI, PEFI, UI, DSOI

- 4” Depth of investigation
- 3 detectors:
- **count rates being compared to signatures in a database**
- **backscatter detector** is closest to source
- 2-in vertical resolution
- better in laminated sections
- **pad better articulated**: better contact with formation
- handles rugosity much better





Formation Density Measurements

Measurement Specifications

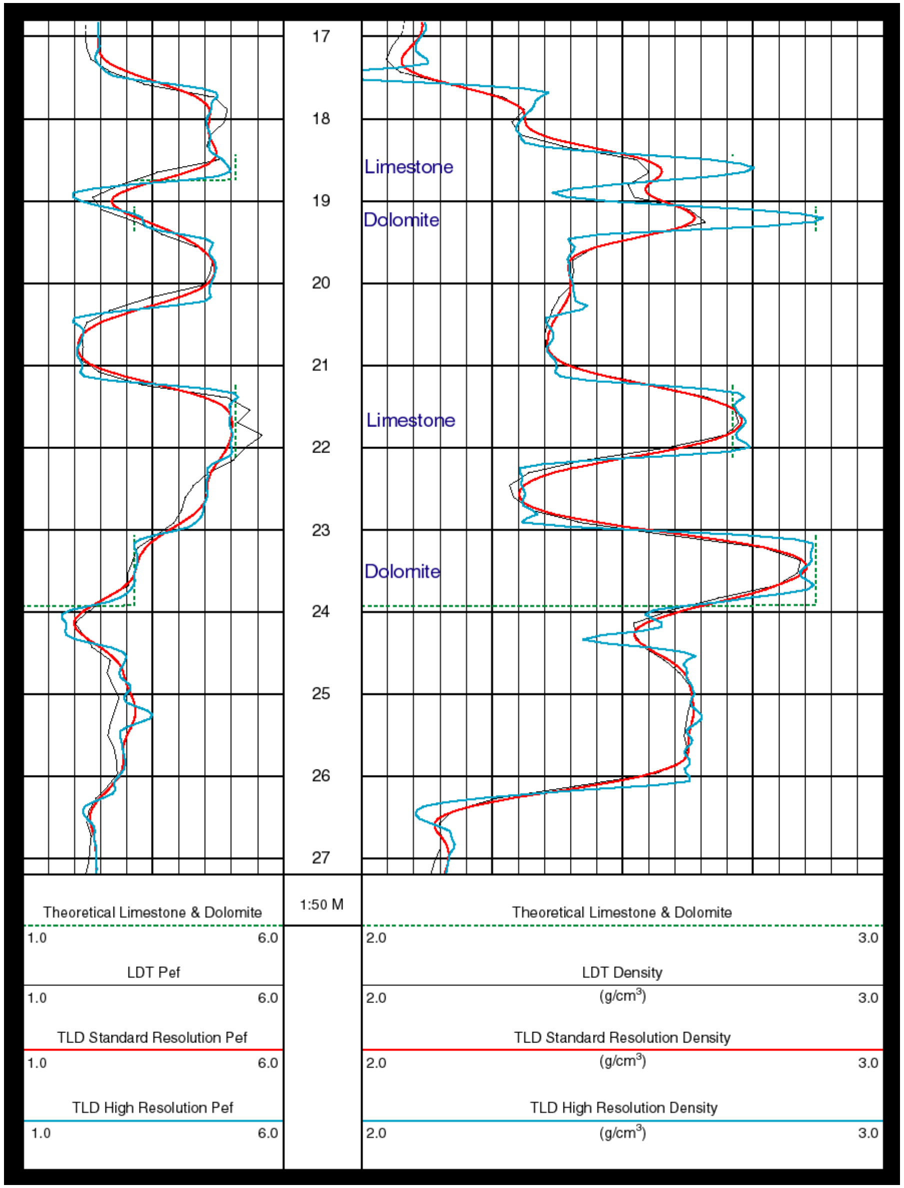
	TLD	LDS	HLDS	SLDT
Output	Bulk density, porosity, PEF, caliper	Bulk density, porosity, PEF, caliper	Bulk density, porosity, PEF, caliper	Bulk density, porosity, PEF
Logging speed	Standard: 3,600 ft/h [1,097 m/h] High resolution: 1,800 ft/h [549 m/h]	Standard: 1,800 ft/h [549 m/h] High resolution: 900 ft/h [274 m/h] High speed: 3,600 ft/h [1,097 m/h]	Standard: 1,800 ft/h [549 m/h] High resolution: 900 ft/h [274 m/h] High speed: 3,600 ft/h [1,097 m/h]	1,800 ft/h [549 m/h]
Range of measurement	Bulk density: 1.04 to 3.3 g/cm^3 PEF: 0.9 to 10 Caliper: 22 in [55.88 cm]	Bulk density: 1.3 to 3.05 g/cm^3 PEF: 1 to 6 Caliper: 16 in [40.64 cm]	Bulk density: 2 to 3 g/cm^3 PEF: 1 to 6 Caliper: 16 in [40.64 cm]	Bulk density: 1.3 to 3.05 g/cm^3 PEF: 1 to 6.2 Caliper: 3 to 9 in [7.62 to 22.86 cm]
Vertical resolution	Density: 18 in [45.72 cm]	Density: 15 in [38.10 cm]	Density: 15 in [38.10 cm]	Density: 15 in [38.10 cm]
Accuracy	Bulk density: ±0.01 g/cm^3† (accuracy), 0.025 g/cm^3 (repeatability) Caliper: 0.1 in [0.25 cm] (accuracy), 0.05 in [0.127 cm] (repeatability)	Bulk density: ±0.01 g/cm^3 (accuracy), 0.014 g/cm^3 (repeatability) Caliper: 0.25 in [0.64 cm] (accuracy), 0.05 in [0.127 cm] (repeatability)	Bulk density: ±0.01 g/cm^3 (accuracy), 0.014 g/cm^3 (repeatability) Caliper: 0.25 in [0.64 cm] (accuracy), 0.05 in [0.127 cm] (repeatability)	Bulk density: ±0.01 g/cm^3 (accuracy), 0.014 g/cm^3 (repeatability), Caliper: 0.1 in [0.25 cm] (accuracy), 0.05 in [0.127 cm] (repeatability)
Depth of investigation‡	5 in [12.70 cm]	4 in [10.16 cm]	4 in [10.16 cm]	4 in [10.16 cm]
Mud type or weight limitations	Sensitive to barite	Sensitive to barite	Sensitive to barite	Sensitive to barite
Combinability	Part of Platform Express system, combinable with most tools	Combinable with most tools	Combinable with most tools	Part of SlimAccess system
Special applications		Spectral processing of formation gamma ray measurement	HPHT Spectral processing of formation gamma ray measurement	Slim wellbores Short-radius wells Tubing-conveyed logging On tractor

† At 1,800 ft/h [549 m/h] in nonbarite mud
‡ Average values (depth of investigation depends on density)

Mechanical Specifications

	TLD	LDS	HLDS	SLDT
Temperature rating	302 degF [150 degC]	350 degF [177 degC]	500 degF [260 degC]	302 degF [150 degC]
Pressure rating	15,000 psi [103 MPa]	20,000 psi [138 MPa]	25,000 psi [172 MPa]	14,000 psi [97 MPa]
Borehole size—min.	6 in [15.24 cm]	5½ in [13.97 cm]	4½ in [11.43 cm]	3½ in [8.89 cm]
Borehole size—max.	22 in [55.88 cm]	21 in [53.34 cm]	18 in [45.72 cm]	9 in [22.86 cm]
Outside diameter	4.77 in [12.11 cm]	4.5 in [11.43 cm]	3.5 in [8.89 cm]	2.5 in [6.35 cm]
Length	12.26 ft [3.74 m]	11 ft [3.35 m]	12.58 ft [3.83 m]	14.9 ft [4.54 m]
Weight	314 lbm [142 kg]	292 lbm [132 kg]	402 lbm [182 kg]	159 lbm [72 kg]
Tension	50,000 lbf [222,410 N]	30,000 lbf [133,450 N]	30,000 lbf [133,450 N]	50,000 lbf [222,410 N]
Compression	Without stiffener and locked flex head: 4,400 lbf [19,570 N] With stiffener and locked flex head: 8,000 lbf [35,590 N]	5,000 lbf [22,240 N]	5,000 lbf [22,240 N]	14,000 lbf [62,270 N]

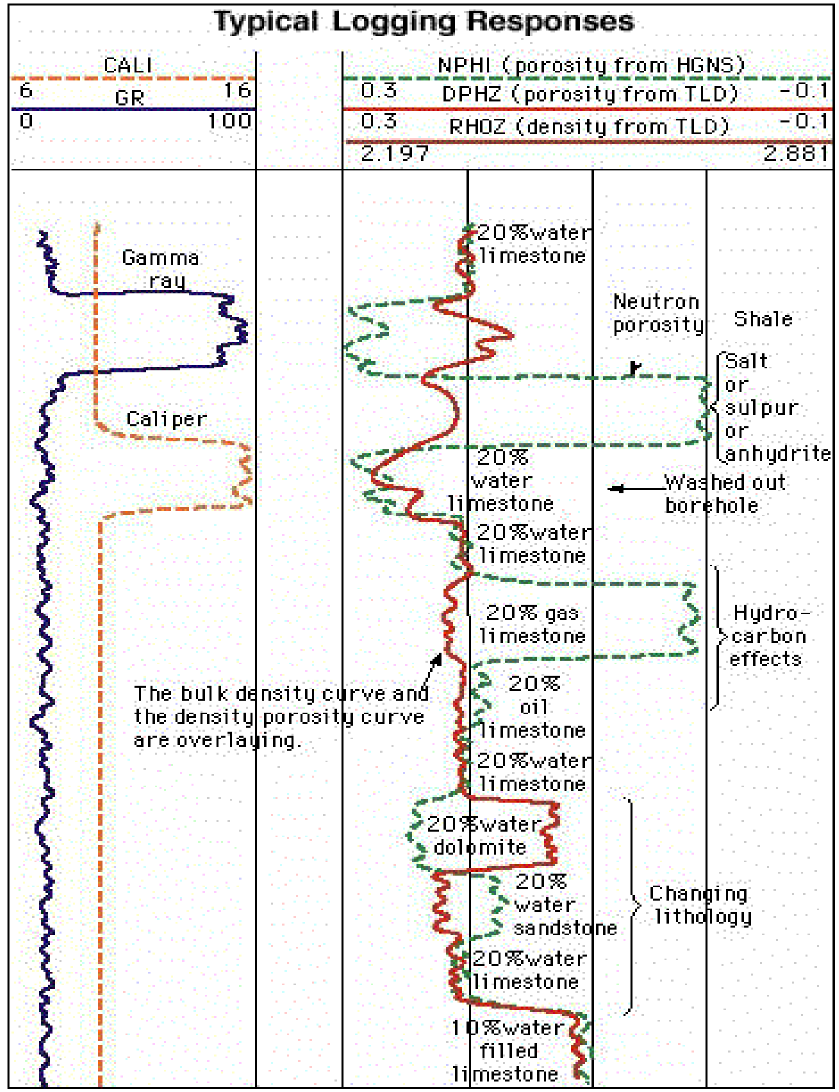
Density Log Example

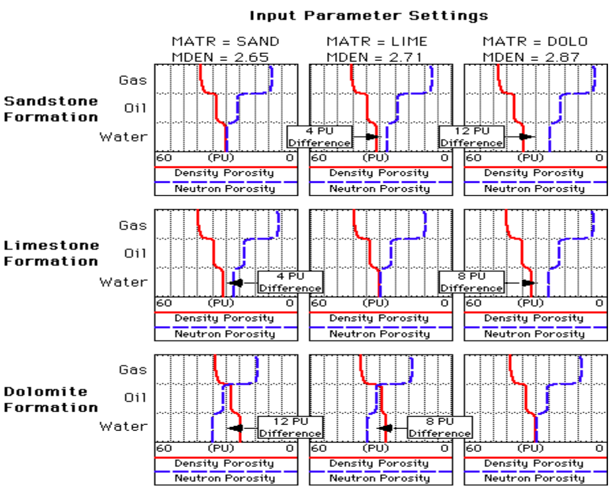


Expected Formation Responses

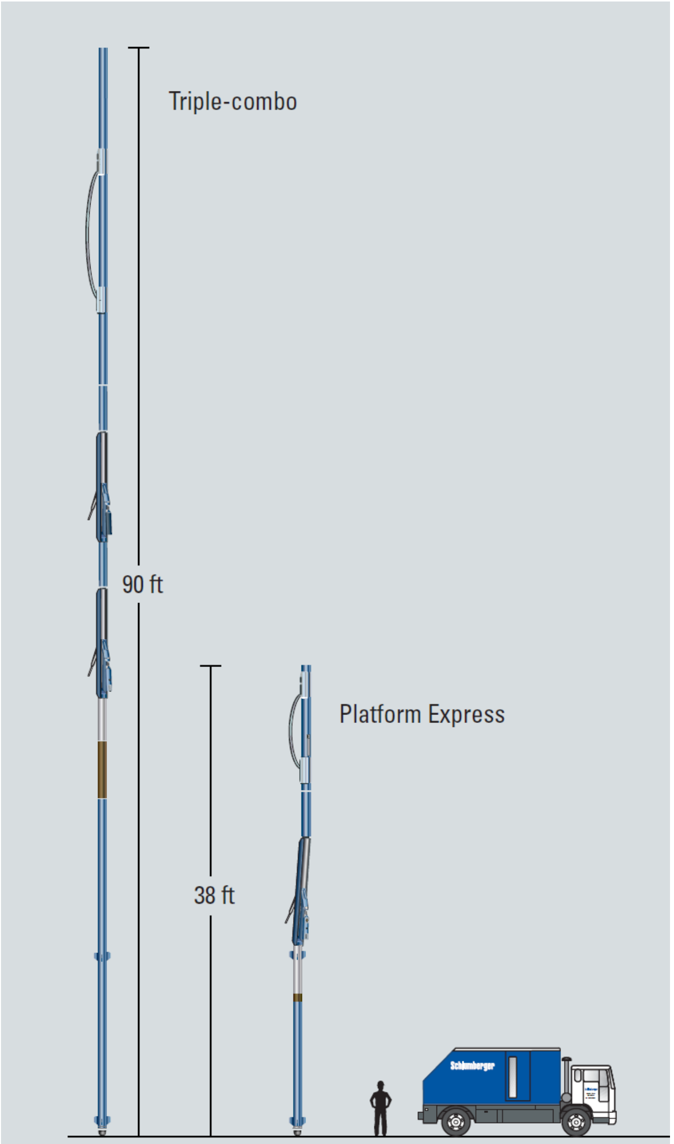
Effect on NPOR and DPHZ

- differing Lithologies
- gas in the pore space
- oil in the pore space
- washouts
- shale formations
- salt formations
- anhydrite, etc…
- In this example, NPOR can replace NPHI and the matrix settings are limestone.

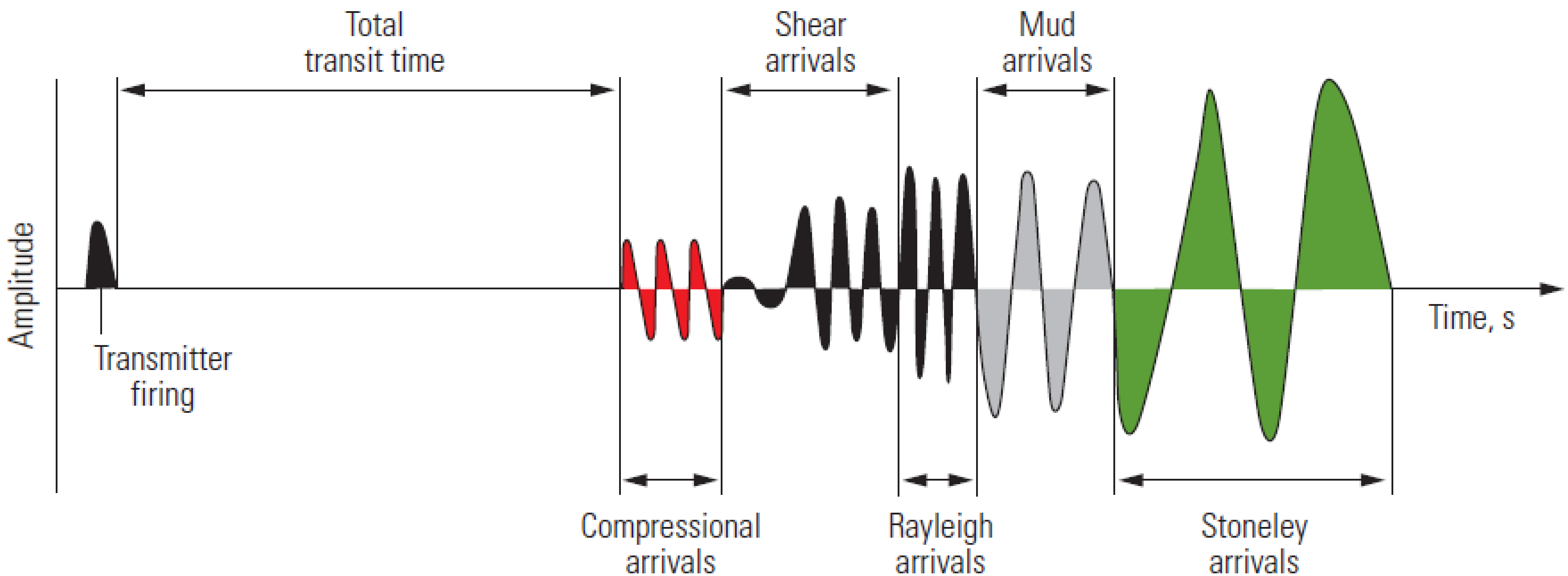




Most Common Logging Suite
The Triple Combo



Monopole Acoustic Wave



Acoustic Measurements
Monopole Acoustic Logging Tools

Measurement Specifications

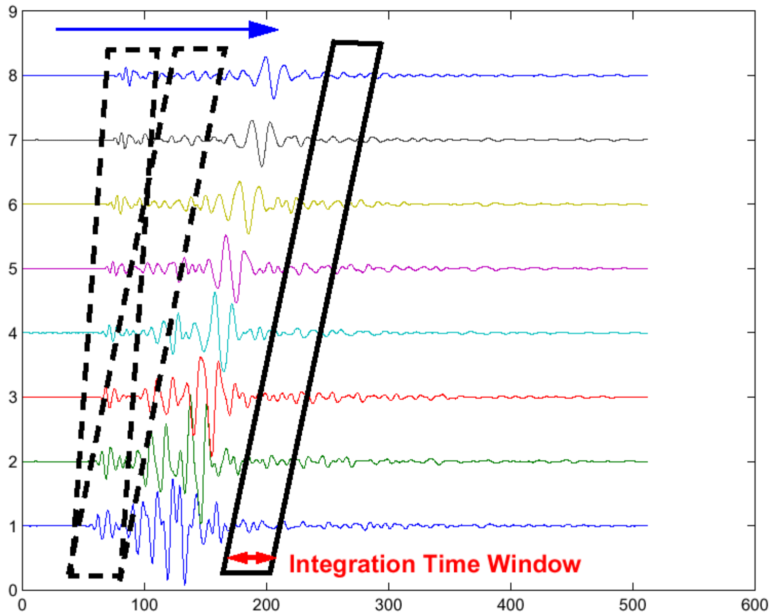
	DSLT and HSLT with BHC or DDBHC Sonde	SSLT and QSLT
Output	All sondes: Compressional Δ*t* SLS-C, SLS-D, and SLS-E: 3-ft [0.91-m] CBL, Variable Density waveforms	Compressional and shear Δ*t*, porosity, waveforms and Variable Density waveforms
Logging speed	3,600 ft/h [1,097 m/h]	3,600 ft/h [1,097 m/h]
Range of measurement	40 to 200 us/ft [131 to 656 us/m]	40 to 400 us/ft [131 to 1,312 us/m]
Vertical resolution		
Compressional Δ*t*	2 ft [0.61 m]	Standard: 2 ft [0.61 m] Short spacing: 6 in [15.24 cm]
Shear Δ*t*	SLS-F 8 to 10 ft [2.43 to 3.05 m] or 10 to 12 ft [3.05 to 3.66 m]: 2 ft [0.61 m]	2 ft [0.61 m]
Cement bond log	Amplitude (mV): 3 ft [0.91 m] Variable Density log: 5 ft [1.52 m]	Amplitude (mV): 3 ft [0.91 m] Variable Density log: 5 ft [1.52 m]
Accuracy	Δ*t* : ±2 us/ft [±6.6 us/m]	Δ*t* : ±2 us/ft [±6.6 us/m]
Depth of investigation	3 in [7.62 cm]	3 in [7.62 cm]
Mud type or weight limitations	None	None
Combinability	Combinable with most services	Combinable with most services
Special applications		Run on wireline, drillpipe conveyed, or coiled tubing conveyed

Mechanical Specifications

	DSLT	HSLT	SSLT	QSLT
Temperature rating	302 degF [150 degC]	500 degF [260 degC]	302 degF [150 degC]	500 degF [260 degC]
Pressure rating	20,000 psi [138 MPa]	25,000 psi [172 MPa]	14,000 psi [97 MPa]	30,000 psi [207 MPa]
Borehole size—min.	4⅝ in [11.75 cm]	4¾ in [12.07 cm]	3½ in [8.89 cm]	4 in [10.16 cm]
Borehole size—max.	18 in [45.72 cm]	18 in [45.72 cm]	8 in [20.32 cm]	8 in [20.32 cm]
Outside diameter	3⅝ in [9.21 cm]	3⅞ in [9.84 cm]	2½ in [6.35 cm]	3 in [7.62 cm]
Length	SLS-D: 18.73 ft [5.71 m] SLS-F: 23.81 ft [7.26 m]	With HSLS-W sonde: 25.5 ft [7.77 m]	23.1 ft [7.04 m]	23 ft [7.01 m] With inline centralizer: 29.9 ft [9.11 m]
Weight	SLS-D: 273 lbm [124 kg] SLS-F: 353 lbm [160 kg]	With HSLS-W sonde: 440 lbm [199 kg]	232 lbm [105 kg]	270 lbm [122 kg]
Tension	29,700 lbf [132,110 N]	29,700 lbf [132,110 N]	13,000 lbf [57,830 N]	13,000 lbf [57,830 N]
Compression	1,650 lbf [7,340 N]	With HSLS-W sonde: 2,870 lbf [12,770 N] With HSLS-Z sonde: 1,650 lbf [7,340 N]	4,400 lbf [19,570 N]	4,400 lbf [19,570 N]

Slowness Processing Principle

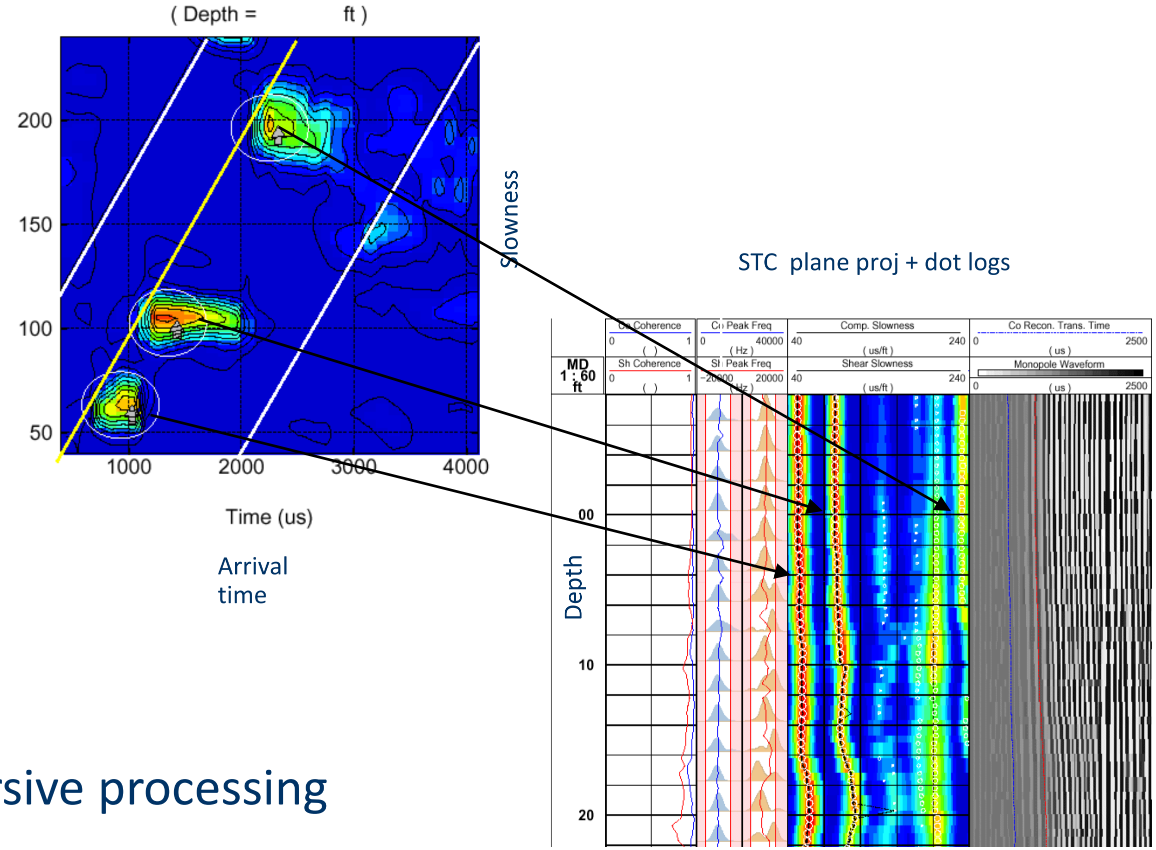
Varying moveout



Varying time

ST Plane at depth Z1 ft (Semblance Contour Plot)

STC plane proj + dot logs

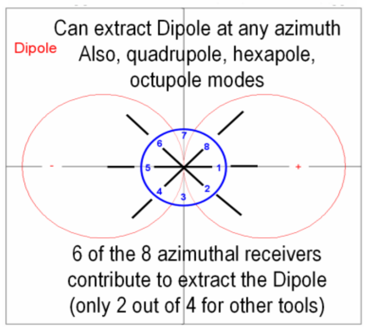


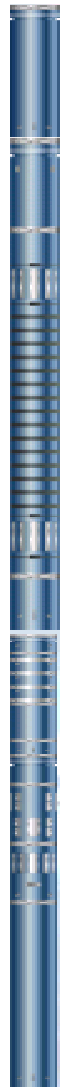
Arrival time

+ Dispersive processing

Sonic Scanner

8 azimuthal segments/receiver





Upper Mono Tx

13 receivers

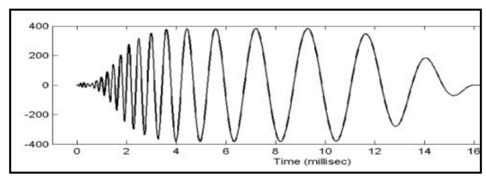
Lower Mono Tx

Bhc, Cbl

Shear — 2 Dipoles

Comp.& Stoneley — 1 Far Monopole

Chirp Firing

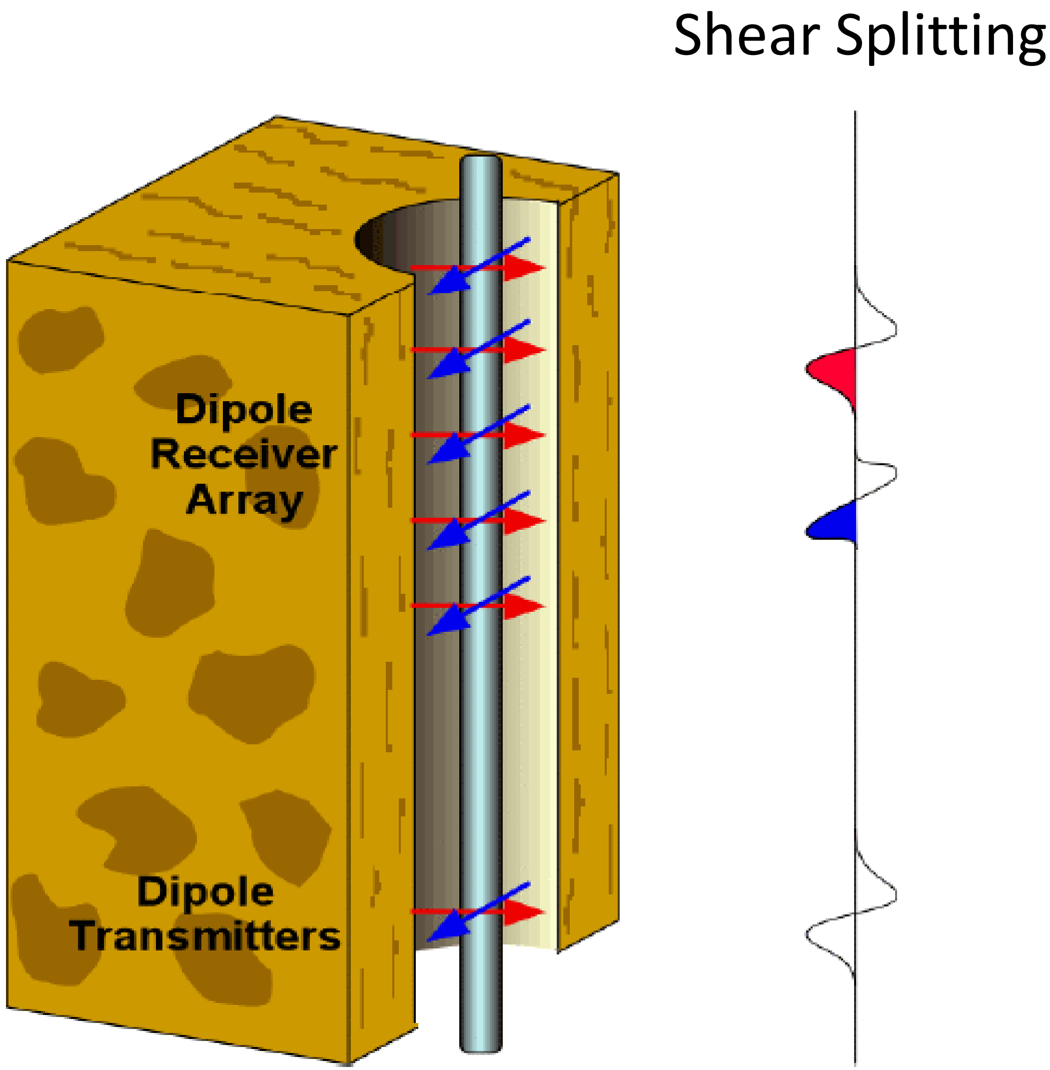


300 hz to 9,000 hz

Schlumberger Confidential

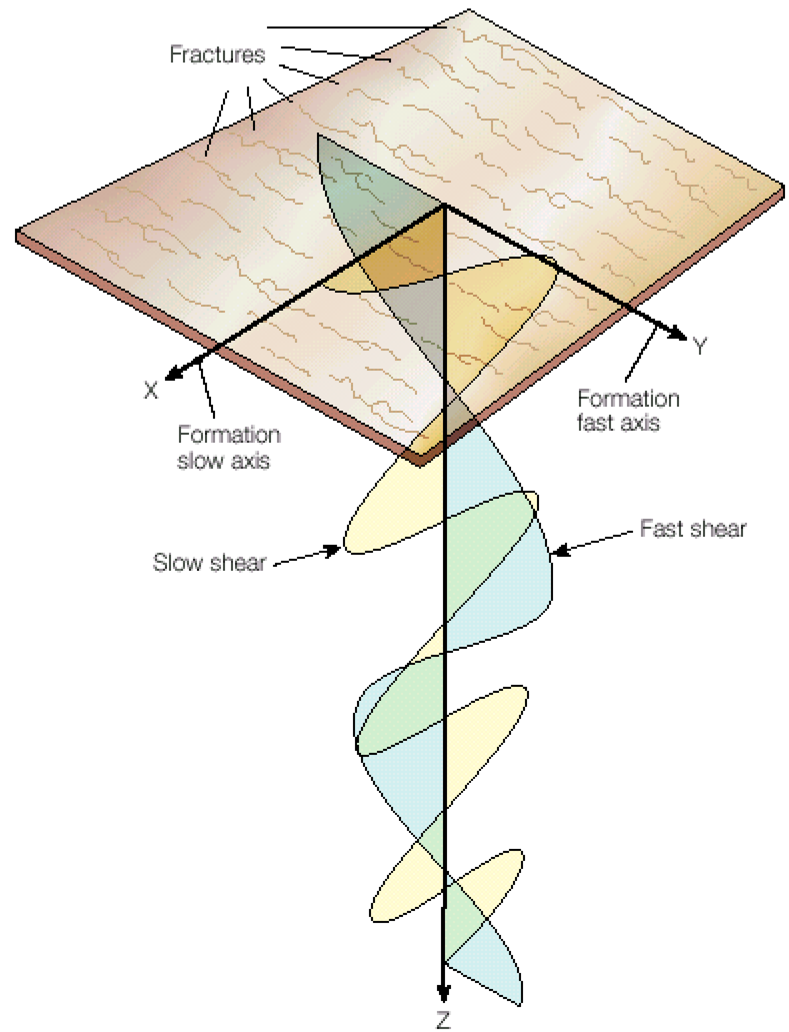
Sonic Scanner Anisotropy

Anisotropy: Shear Splitting



Formation Shear Anisotropy

Shear-waves split and travel in anisotropic formation with different speeds along the formation anisotropy



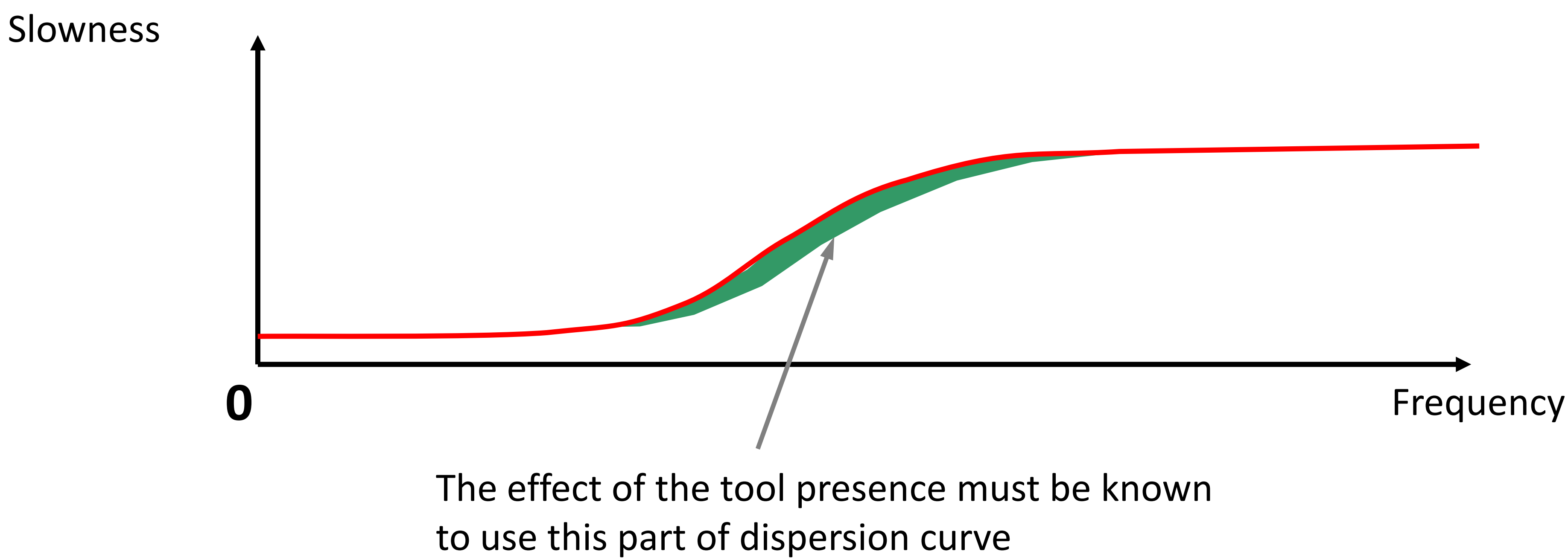
Anisotropy may be caused by

- fractures, micro-cracks
- stress anisotropy
- deposition (thin beds)

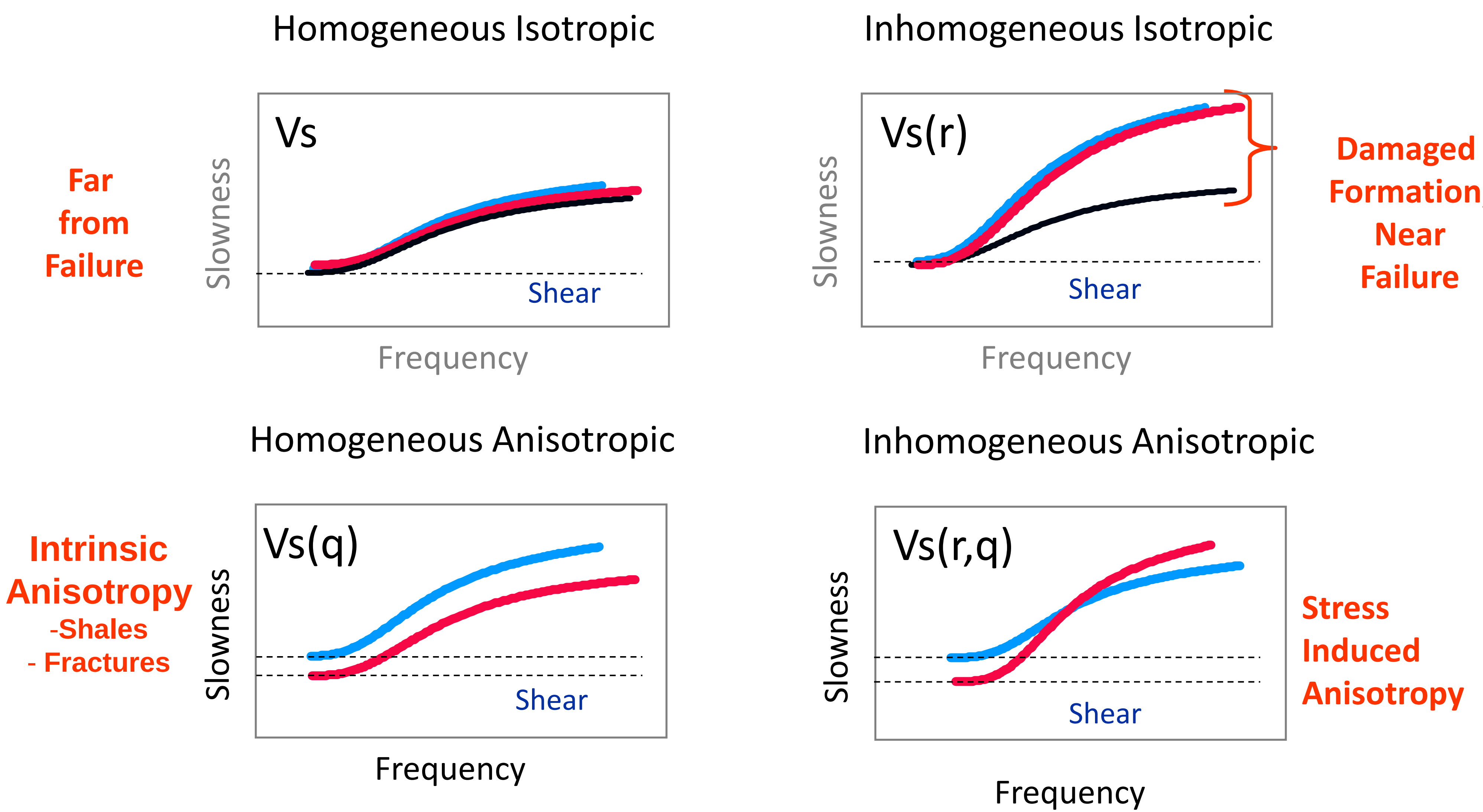
Case of fracture anisotropy:
fastest shear-wave component is polarized along the fracture strike or maximum stress direction

Flexural Dispersion and Tool Presence

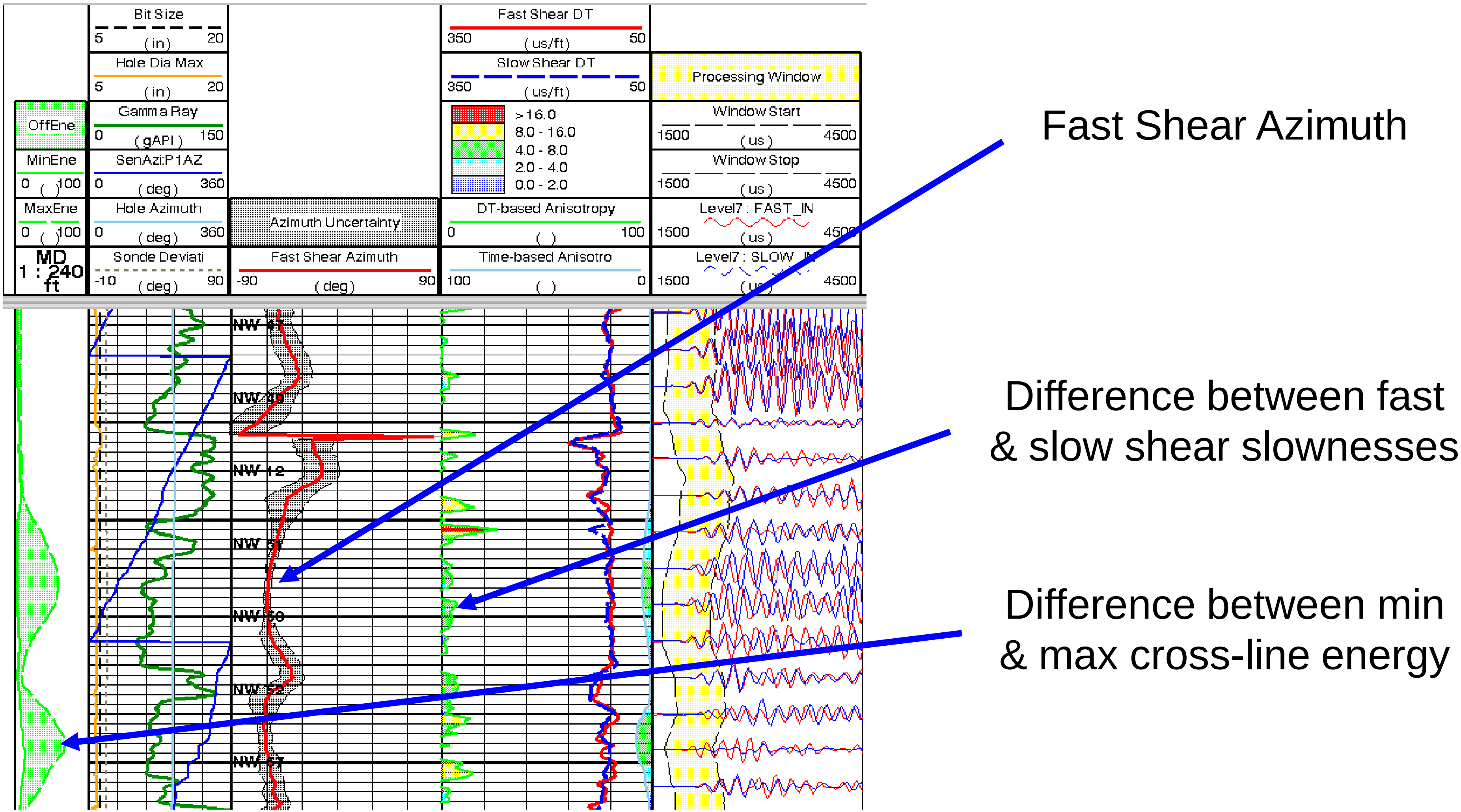
Sonic Scanner is fully characterized for tool presence in the borehole
This is critical to evaluate the anisotropy classification



Dispersion Curves :

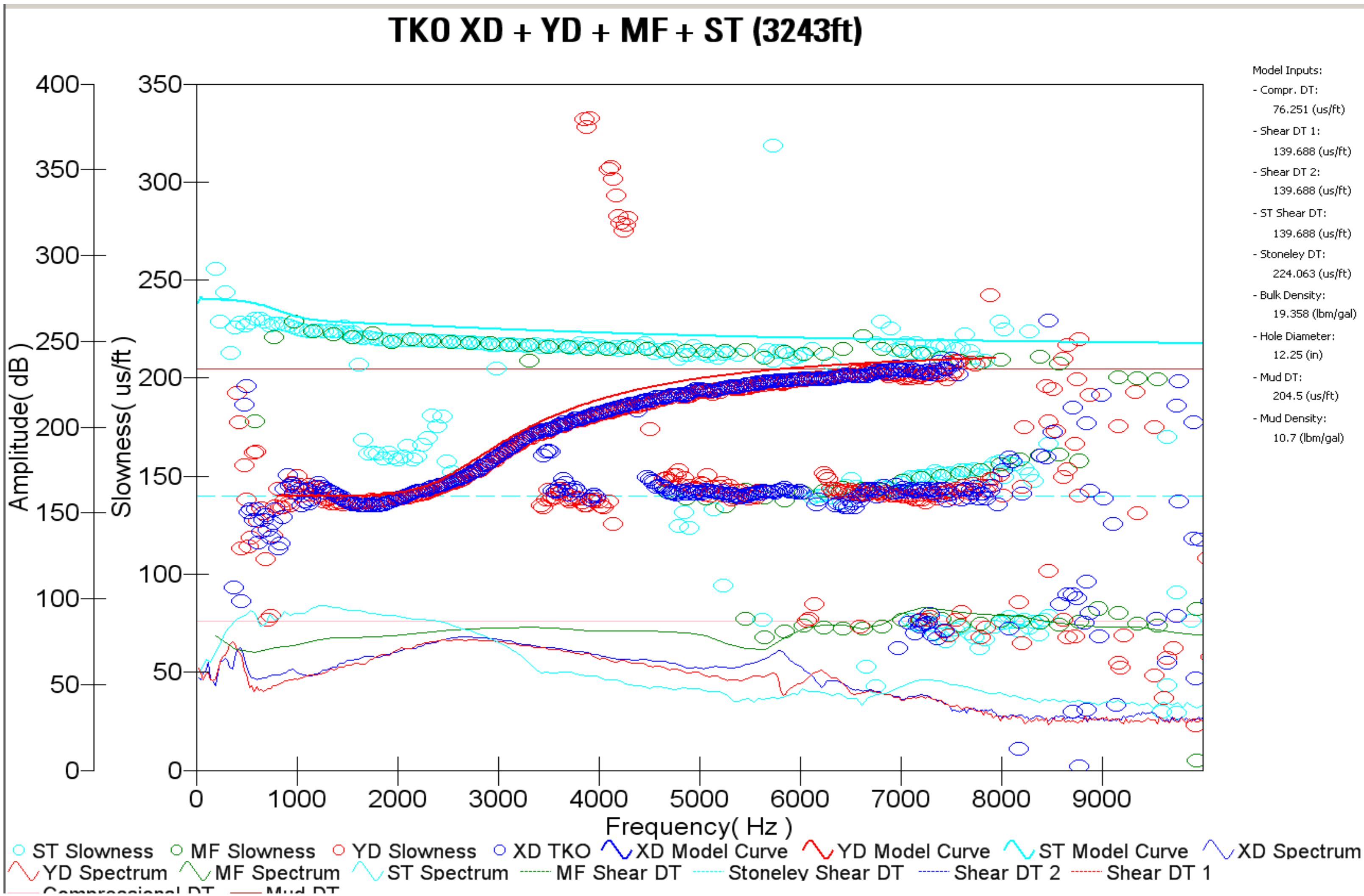


Standard Anisotropy Log

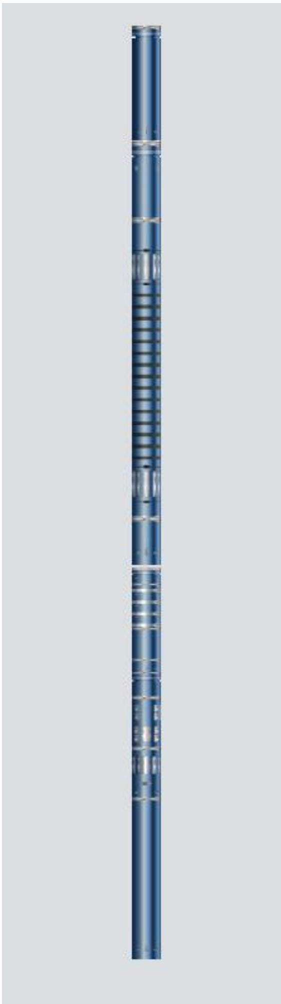


Dispersion Plot

MF, St
Xd
Yd



Acoustic Measurements
Sonic Scanner



Measurement Specifications	
	Sonic Scanner Tool
Output	Compressional and shear Δ*t*, full waveforms, cement bond quality waveforms, anisotropy characterization
Logging speed	Max.: 3,600 ft/h [1,097 m/h]
Range of measurement	Standard shear slowness: <1,500 us/ft [<4,920 us/m]
Vertical resolution	<6 ft [<1.82 m] processing resolution for 6-in [15.24-cm] sampling rate
Accuracy	Δ*t* for up to 14-in [35.56-cm] hole size: 2 us/ft [6.56 us/m] or 2% Δ*t* for >14-in [>35.56-cm] hole size: 5 us/ft [16.40 us/m] or 5%
Depth of investigation	Typical presentation of up to 7 borehole radii
Mud type or weight limitations	None
Combinability	Fully combinable with other tools

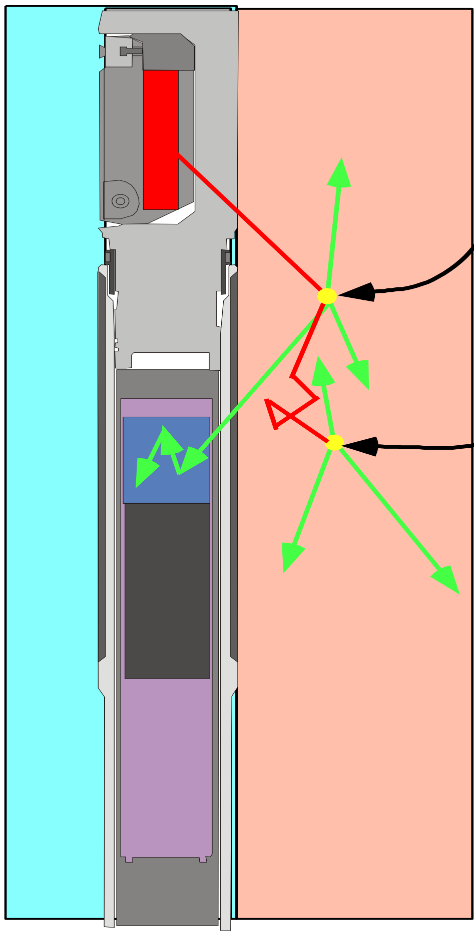
Mechanical Specifications	
	Sonic Scanner Tool
Temperature rating	350 degF [177 degC]
Pressure rating	20,000 psi [138 MPa]
Borehole size—min.	4.75 in [12.07 cm]
Borehole size—max.	22 in [55.88 cm]
Outside diameter	3.625 in [9.21 cm]
Length	41.28 ft [12.58 m] (including isolation joint) Basic toolstring (near monopoles only): 22 ft [6.71 m]
Weight	844 lbm [383 kg] (including isolation joint) Basic toolstring: 413 lbm [187 kg]
Tension	35,000 lbf [155,690 N]
Compression	3,000 lbf [13,340 N]

Dynamic Elastic Properties

v	Poisson's Ratio	$\frac{\text{Lateral strain}}{\text{Longitudinal strain}}$	$\frac{1/2\,(DTS / DTC)^2 - 1}{(DTS / DTC)^2 - 1}$
G	Shear Modulus	$\frac{\text{Applied stress}}{\text{Shear strain}}$	$\frac{\rho_b}{DTS^2}$
E	Young's Modulus	$\frac{\text{Applied uniaxial stress}}{\text{Normal strain}}$	2G (1 + v)
K_b	Bulk Modulus	$\frac{\text{Hydrostatic pressure}}{\text{Volumetric strain}}$	$\rho_b \left[\frac{1}{DTC2} - \frac{4}{3DTS2} \right] \times a$
C_b	Bulk Compressibility (with porosity)	$\frac{\text{Volumetric deformation}}{\text{Hydrostatic pressure}}$	$\frac{1}{K_b}$

Note: coefficient a = 1.34×10^{10} if ρ_b in g/cm^3 and DT in µs/ft.

Elemental Capture Spectroscopy
What Do We Measure ?

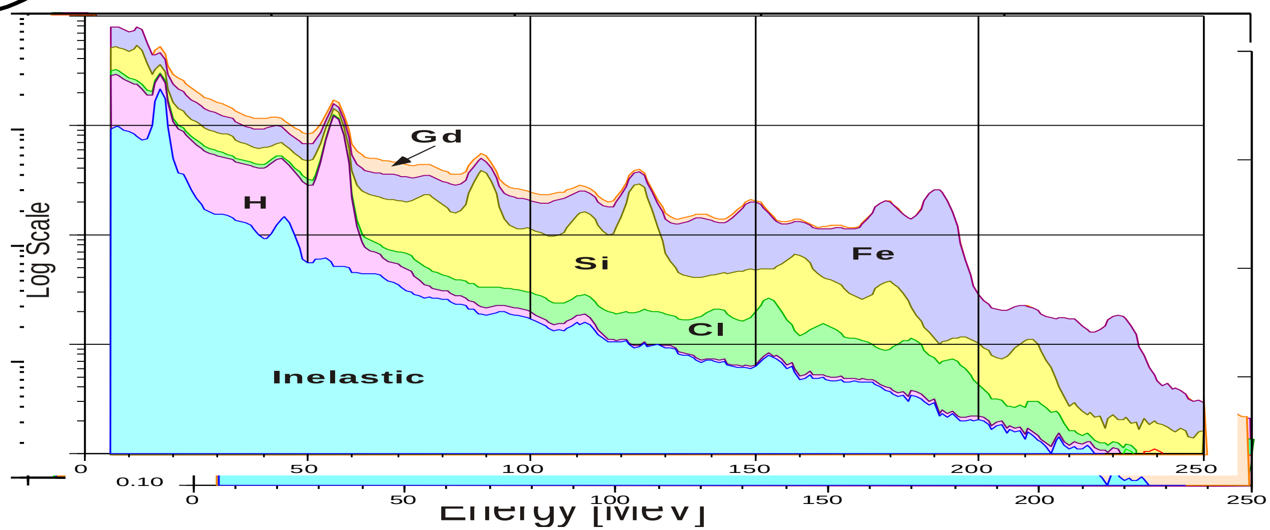


4 MeV neutron interacts with fomation:

Inelastic Interaction (multiple gamma-rays)

Slowing down of neutron through multiple scattering

Neutron Capture (multiple gamma-rays)



Geochemical Measurement: Elemental Capture Spectroscopy

ECS

Measurement Specifications

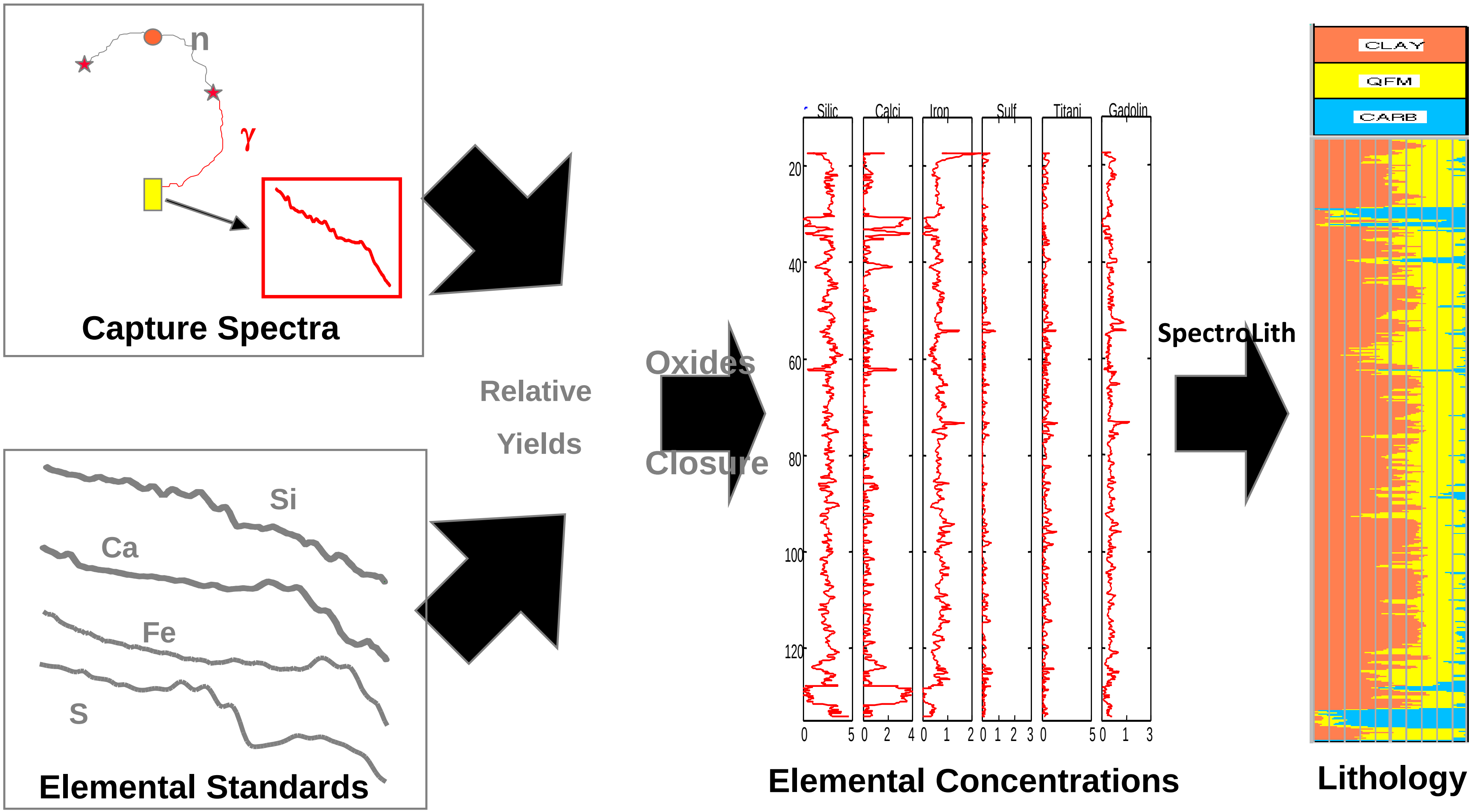
	ECS Sonde
Output	Elemental yields, dry-weight elemental fractions, dry-weight SpectroLith lithology, matrix properties
Logging speed	1,800 ft/h [549 m/h]
Range of measurement	600 keV to 8 MeV
Vertical resolution	18 in [45.72 cm]
Accuracy†	2% – coherence to standards computed
Depth of investigation	9 in [22.86 cm]
Mud type or weight limitations	None
Combinability	Combinable with most tools
Special applications	Automatic wellsite petrophysical interpretation

† Elemental statistical uncertainty at nominal conditions (1,800-ft/h logging speed, resolution degradation factor of 5, 16,000-cps count rate, and closure normalization factor of 3): Si 2.16%, Ca 2.19%, Fe 0.36%, S 1.04%, Ti 0.10%, and Gd 3.48 ppm.

Mechanical Specifications

	ECS Sonde
Temperature rating	350 degF [177 degC] 500 degF [260 degC] (internal flask, CO_2 cooling)
Pressure rating	20,000 psi [138 MPa] High-pressure housing: 25,000 psi [172 MPa]
Borehole size—min.	6 in [15.24 cm]
Borehole size—max.	20 in [50.80 cm]
Outside diameter	5.0 in [12.70 cm] High-pressure housing: 5.5 in [13.97 cm]
Length	10.15 ft [3.09 m]
Weight	305 lbm [138 kg]
Tension	50,000 lbf [222,410 N]
Compression	20,000 lbf [88, 960 N]

Capture Gamma-Ray Spectroscopy



Sigma, Inelastic and Capture Spectroscopy
Reservoir Saturation Tool

1 11/16-in RST-A and RST-C

2½-in RST-B and RST-D

Measurement Specifications

	RST and RSTPro Tools
Output	Inelastic and capture yields of various elements, carbon/oxygen ratio, formation capture cross section (sigma), porosity, borehole holdup, water velocity, phase velocity, SpectroLith processing
Logging speed†	Inelastic mode: 100 ft/h [30 m/h] (formation dependent) Capture mode: 600 ft/h [183 m/h] (formation and salinity dependent) RST sigma mode: 1,800 ft/h [549 m/h] RSTPro sigma mode: 3,600 ft/h [1,097 m/h]
Range of measurement	Porosity: 0 to 60 pu
Vertical resolution	15 in [38.10 cm]
Accuracy	Based on hydrogen index of formation
Depth of investigation	10 in [20.54 cm]
Mud type or weight limitations	None
Combinability	RST tool: Combinable with the PL Flagship system and CPLT tool RSTPro tool: Combinable with tools that use the PS Platform telemetry system and CGRS

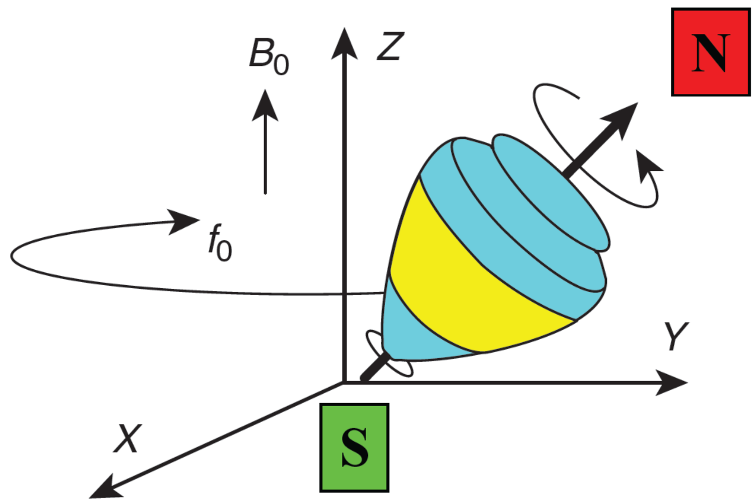
† See Tool Planner application for advice on logging speed

Mechanical Specifications

	RST-A and RST-C	RST-B and RST-D
Temperature rating	302 degF [150 degC] With flask: 400 degF [204 degC]	302 degF [150°C]
Pressure rating	15,000 psi [103 MPa] With flask: 20,000 psi [138 MPa]	15,000 psi [103 MPa]
Borehole size—min.	1 13/16 in [4.60 cm] With flask: 2¼ in [5.72 cm]	2⅞ in [7.30 cm]
Borehole size—max.	9⅝ in [24.45 cm] With flask: 9⅝ in [24.45 cm]	9⅝ in [24.45 cm]
Outside diameter	1.71 in [4.34 cm] With flask: 2⅛ in [5.40 cm]	2.51 in [6.37 cm]
Length	23.0 ft [7.01 m] With flask: 33.7 ft [10.27 m]	22.2 ft [6.76 m]
Weight	101 lbm [46 kg] With flask: 243 lbm [110 kg]	208 lbm [94 kg]
Tension	10,000 lbf [44,480 N]	10,000 lbf [44,480 N]
Compression	1,000 lbf [4,450 N]	1,000 lbf [4,450 N]

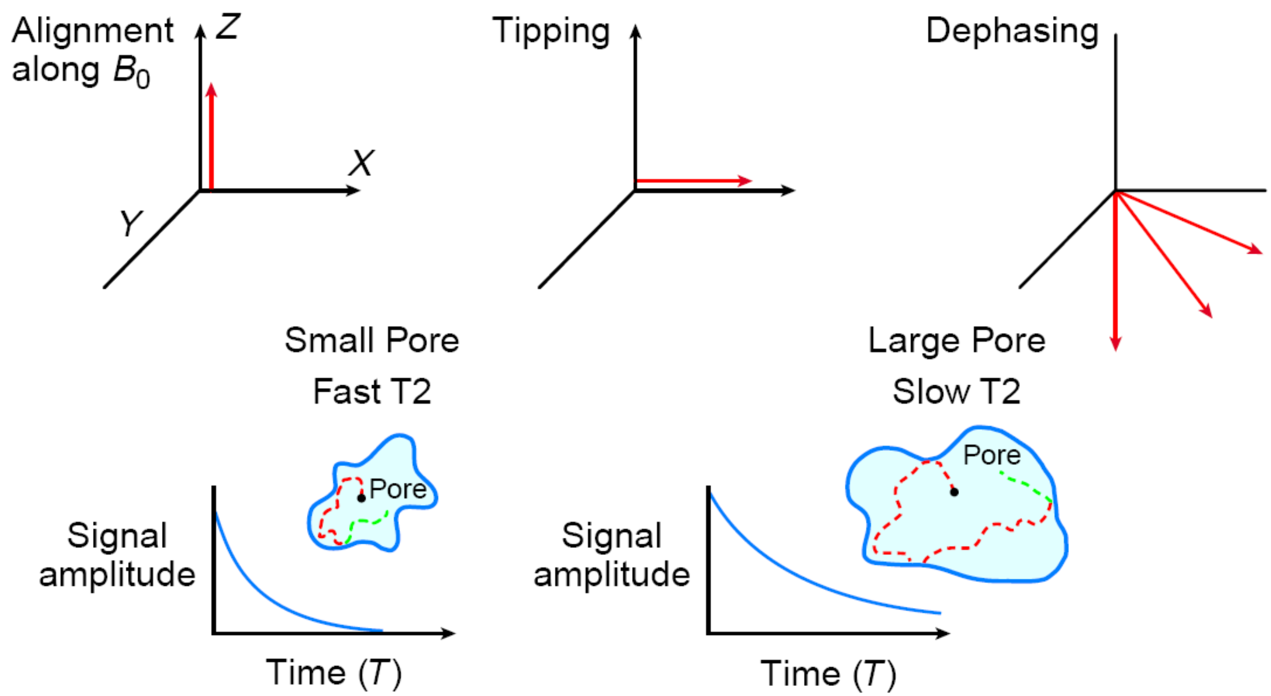
NMR Measurement

NMR Measurement



- Hydrogen nuclei have angular momentum and magnetic moment.
- Hydrogen nuclei align themselves in a static magnetic field.
- When tipped out of alignment, hydrogen nuclei behave like a spinning top. Over time, hydrogen nuclei dephase and realign with the static magnetic field.

NMR Measurement



$$1/T_2 = \rho(S/V)$$

T_2 = Transverse relaxation time (msec)

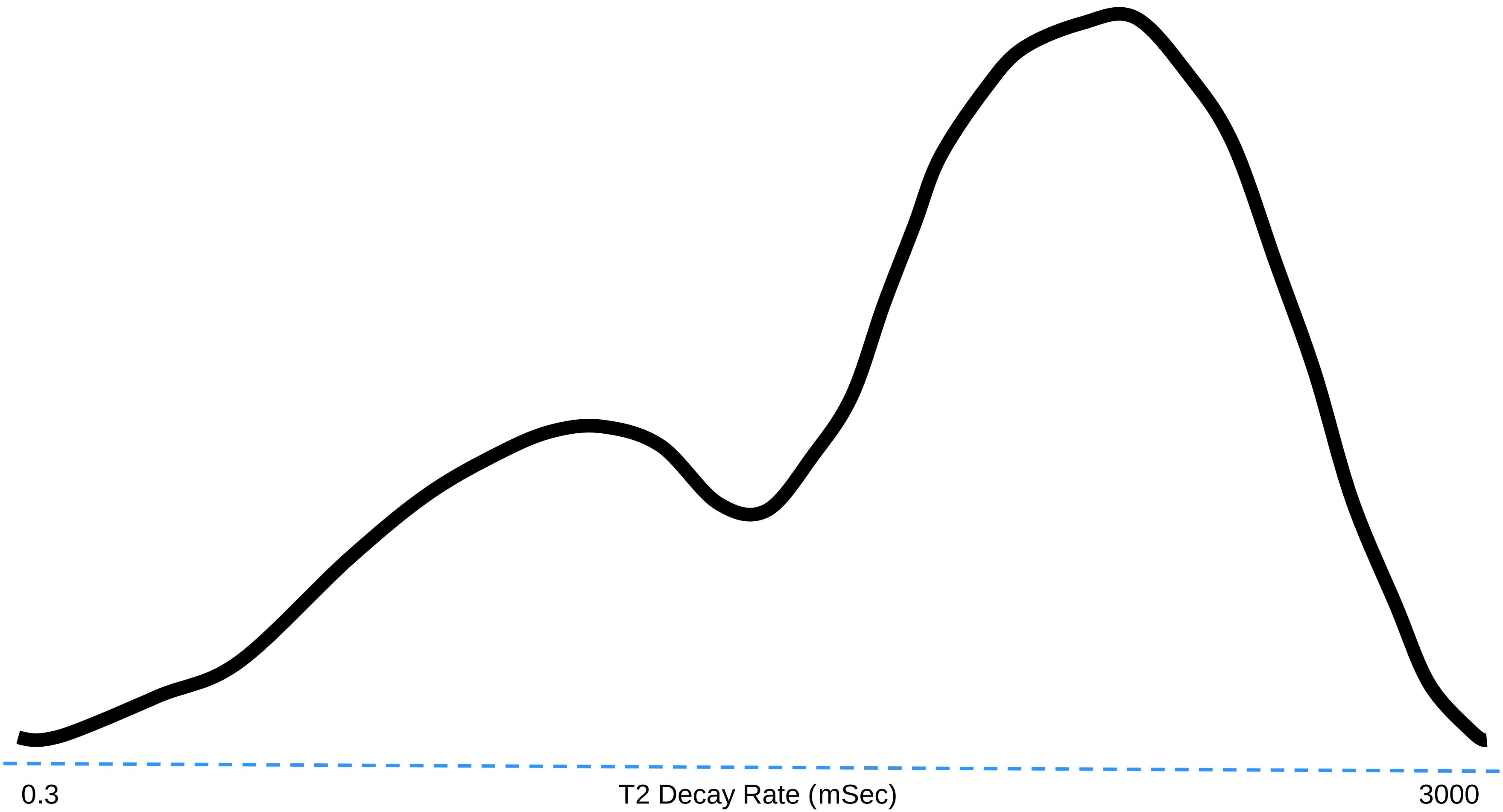
S = Surface area of pore

V = Volume of pore

ρ = Surface relaxivity (5.0 µm/sec sand)
(1.5 µm/sec carbonate)

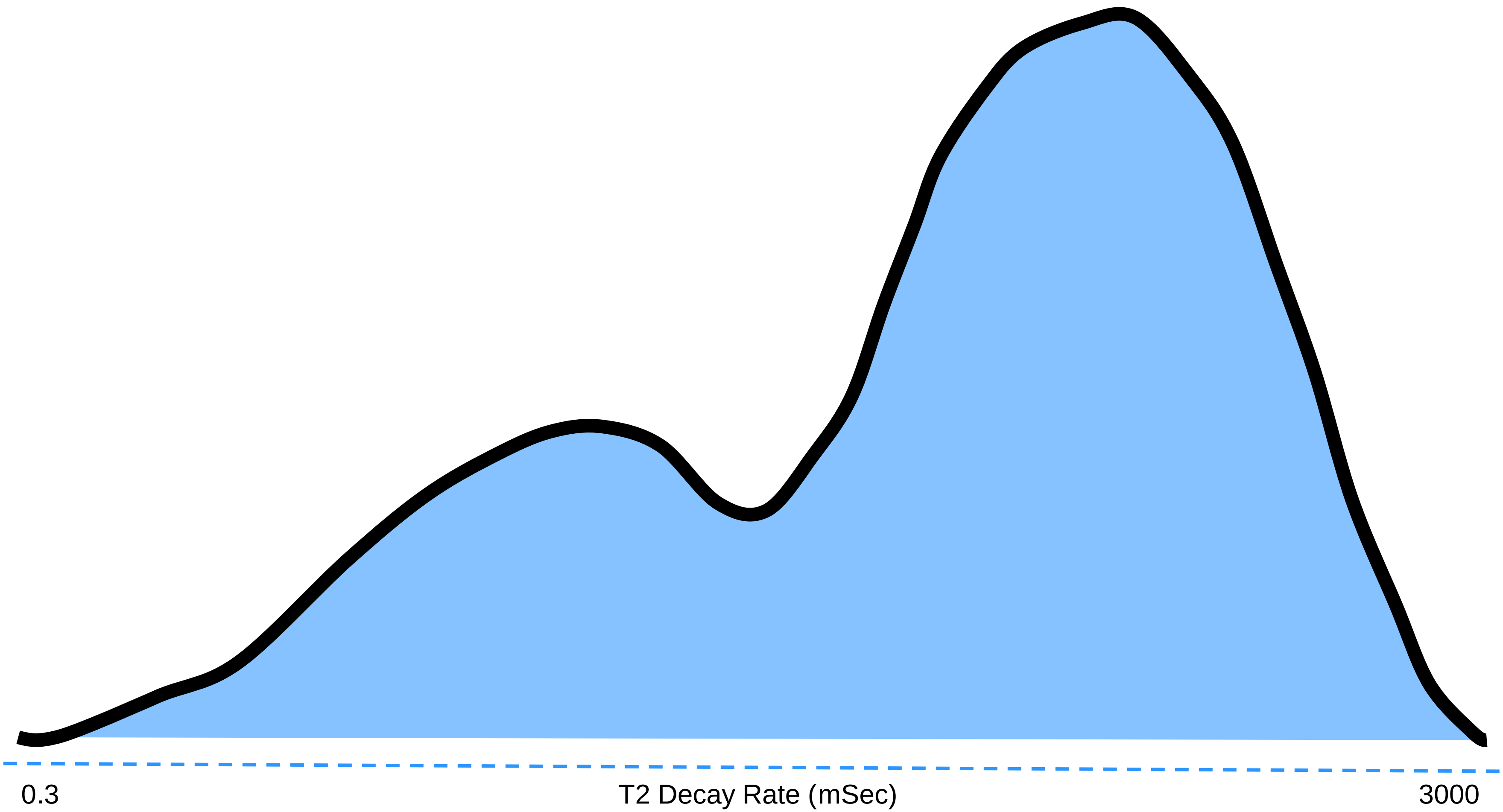
NMR

T2 DISTRIBUTION



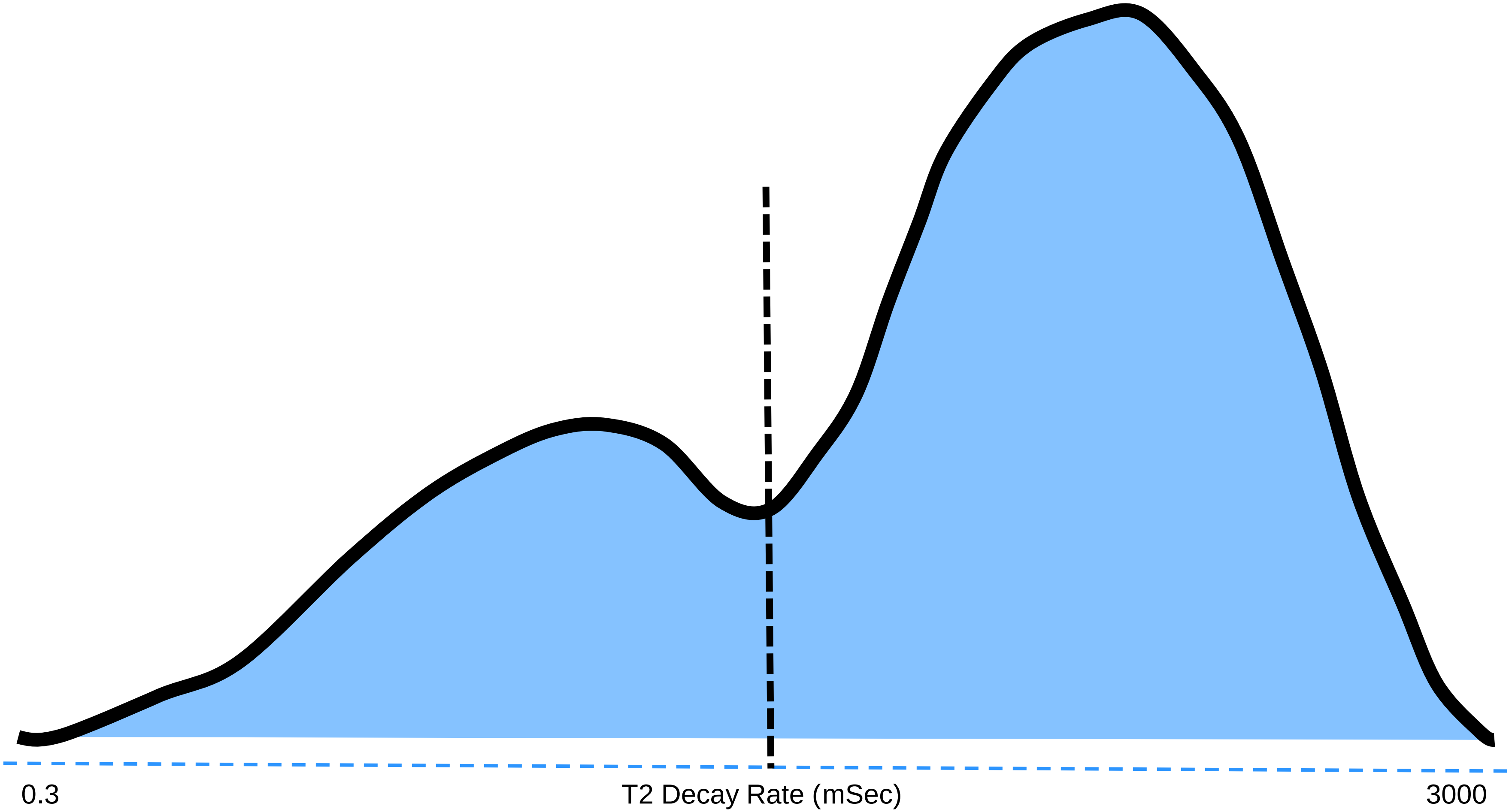
NMR

AREA UNDER THE CURVE IS POROSITY



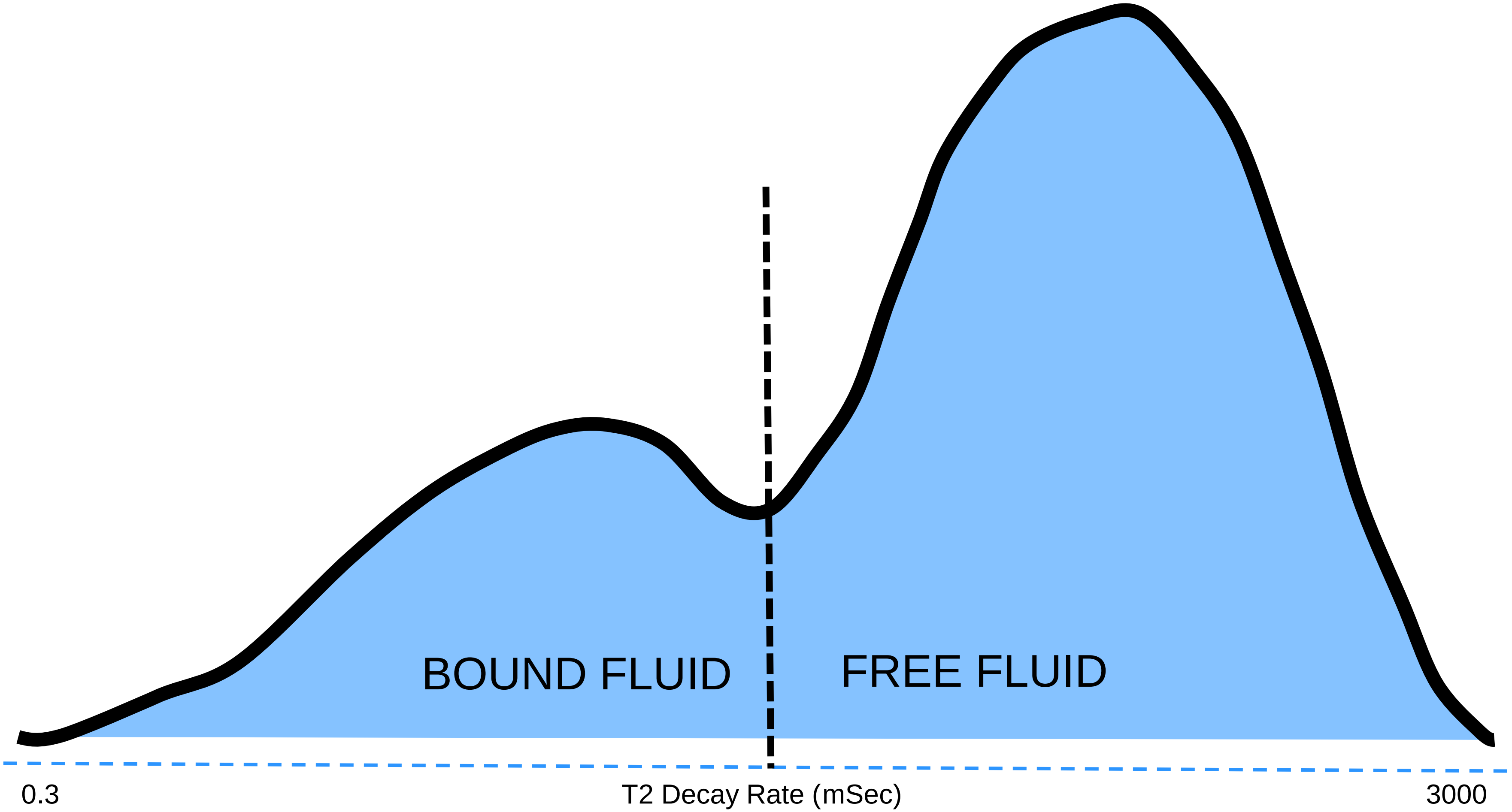
NMR

T2 CUTOFF Separates Bound and Free Fluid

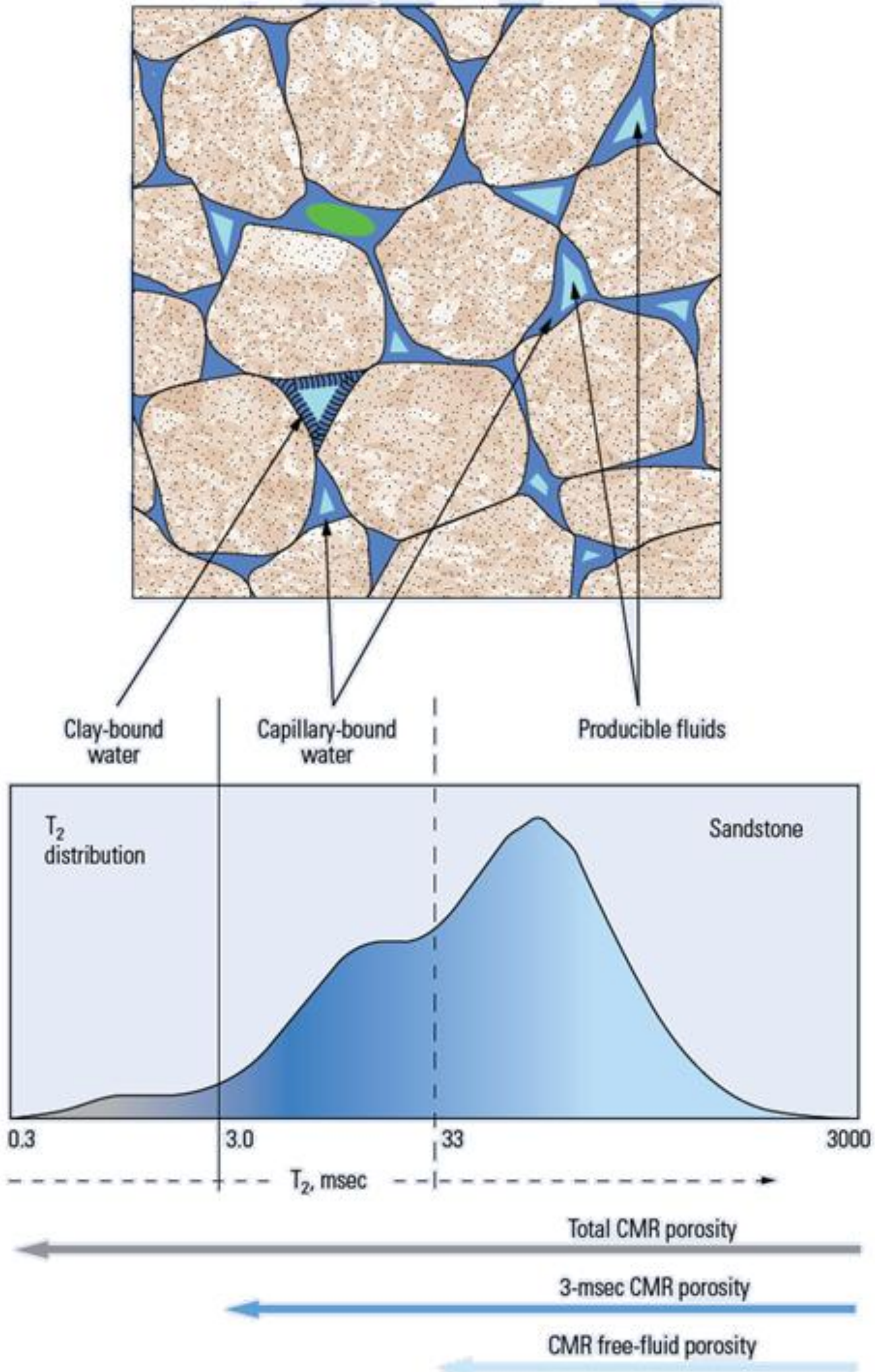


NMR

T2 CUTOFF Separates Bound and Free Fluid

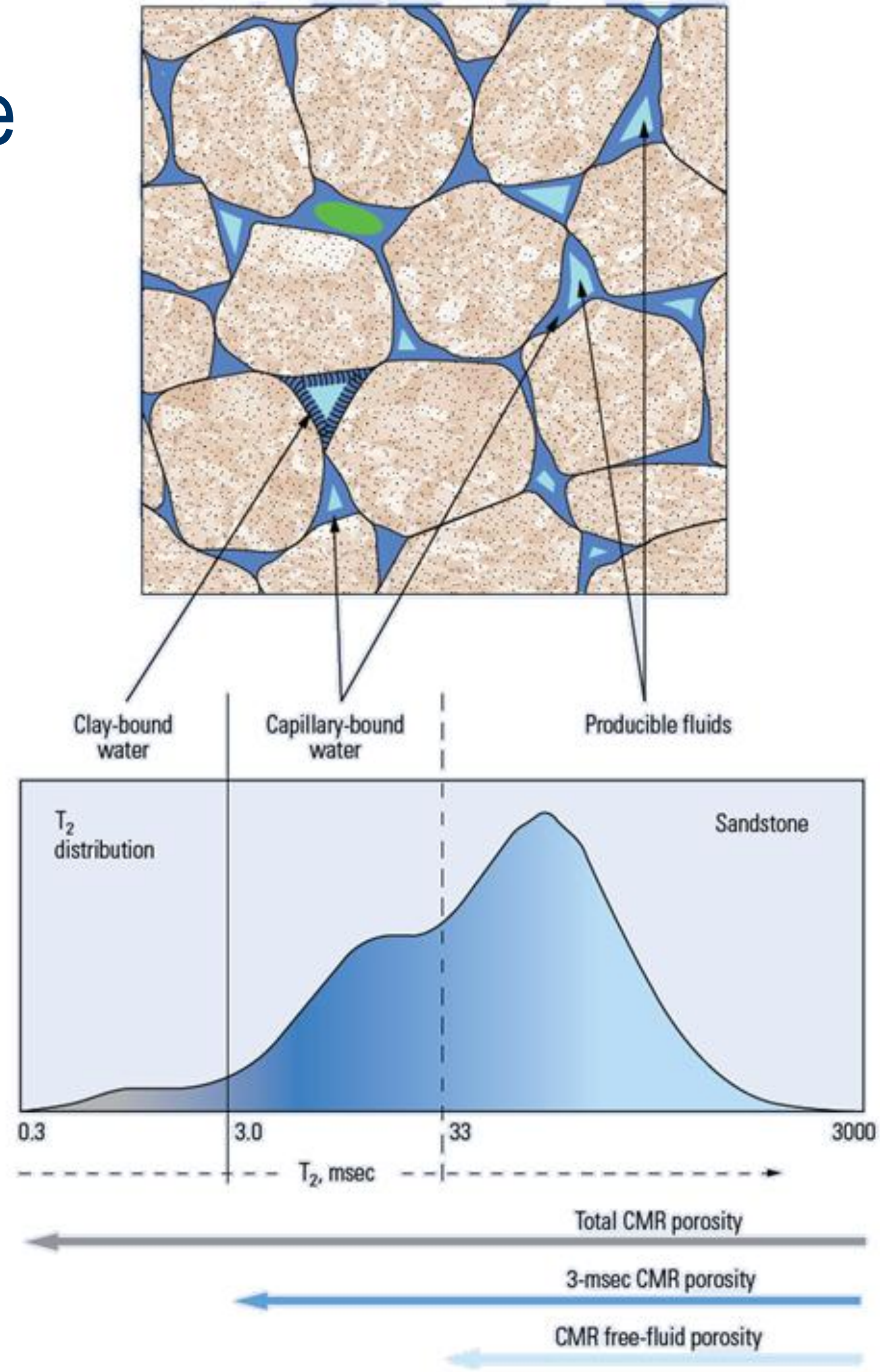


NMR Porosity

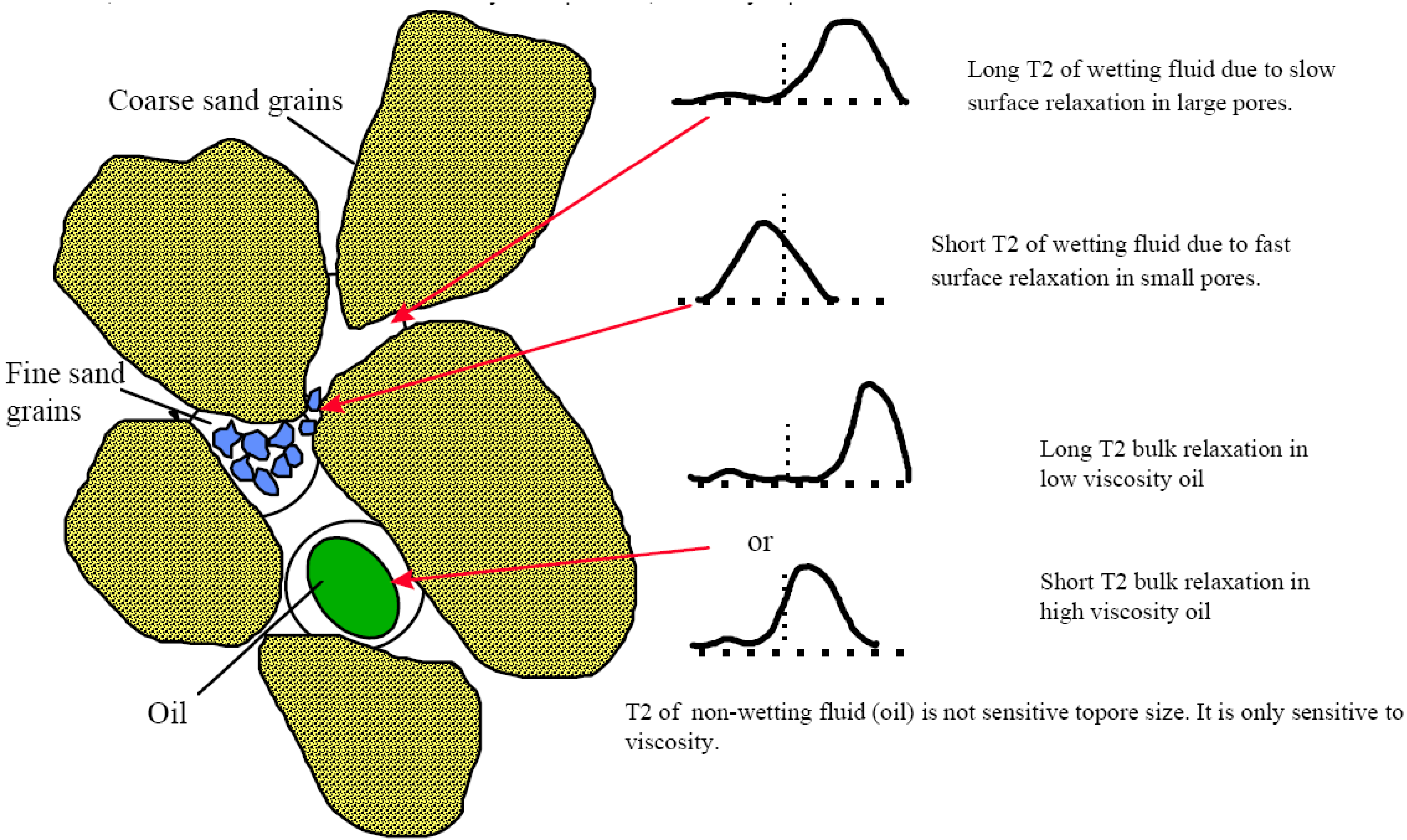


Value of Magnetic Resonance

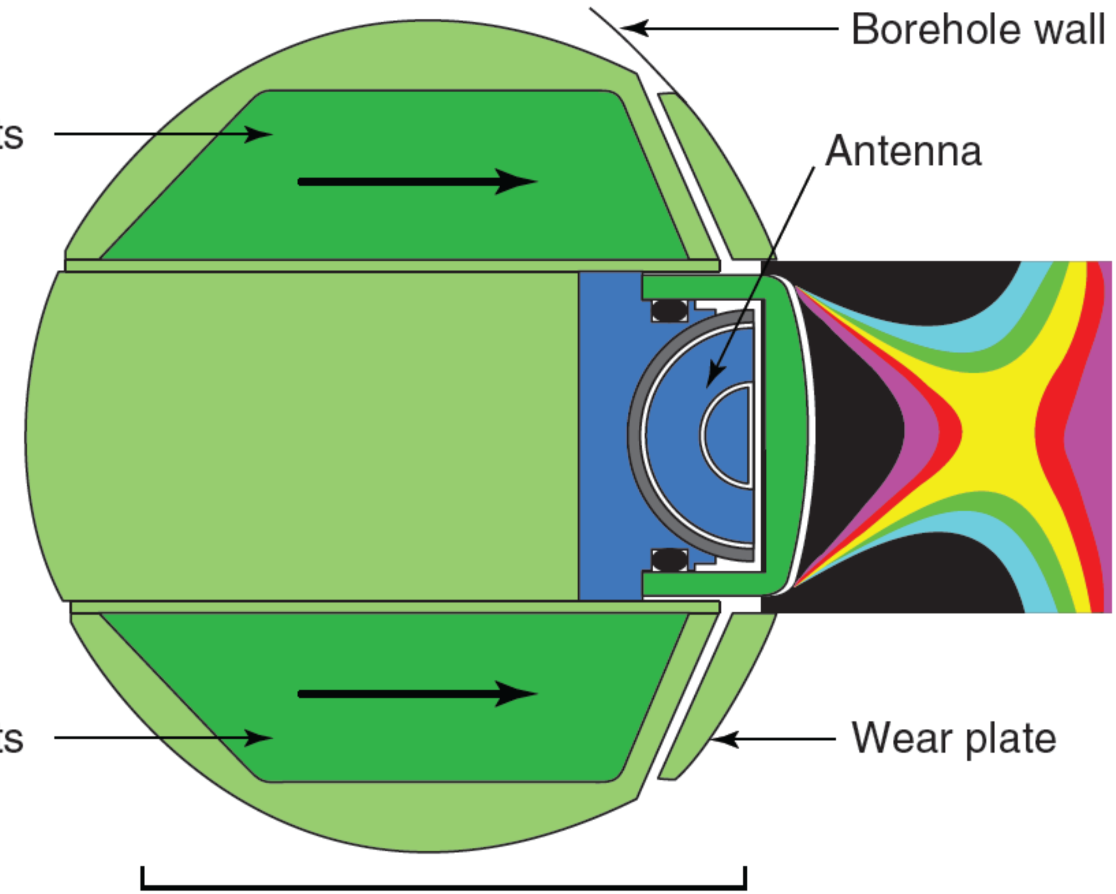
- Lithology Independent Porosity
  - Matrix is invisible
  - Sourceless (no radioactivity)
  - ρ_m, ρ_f not required
- Sensitive to Fluids
  - Hydrogen Index
  - Viscosity
  - Molecular Diffusion
- Sensitive to Pores
  - Irreducible Water Saturation
  - Permeability, K
  - Bound / Free Fluid



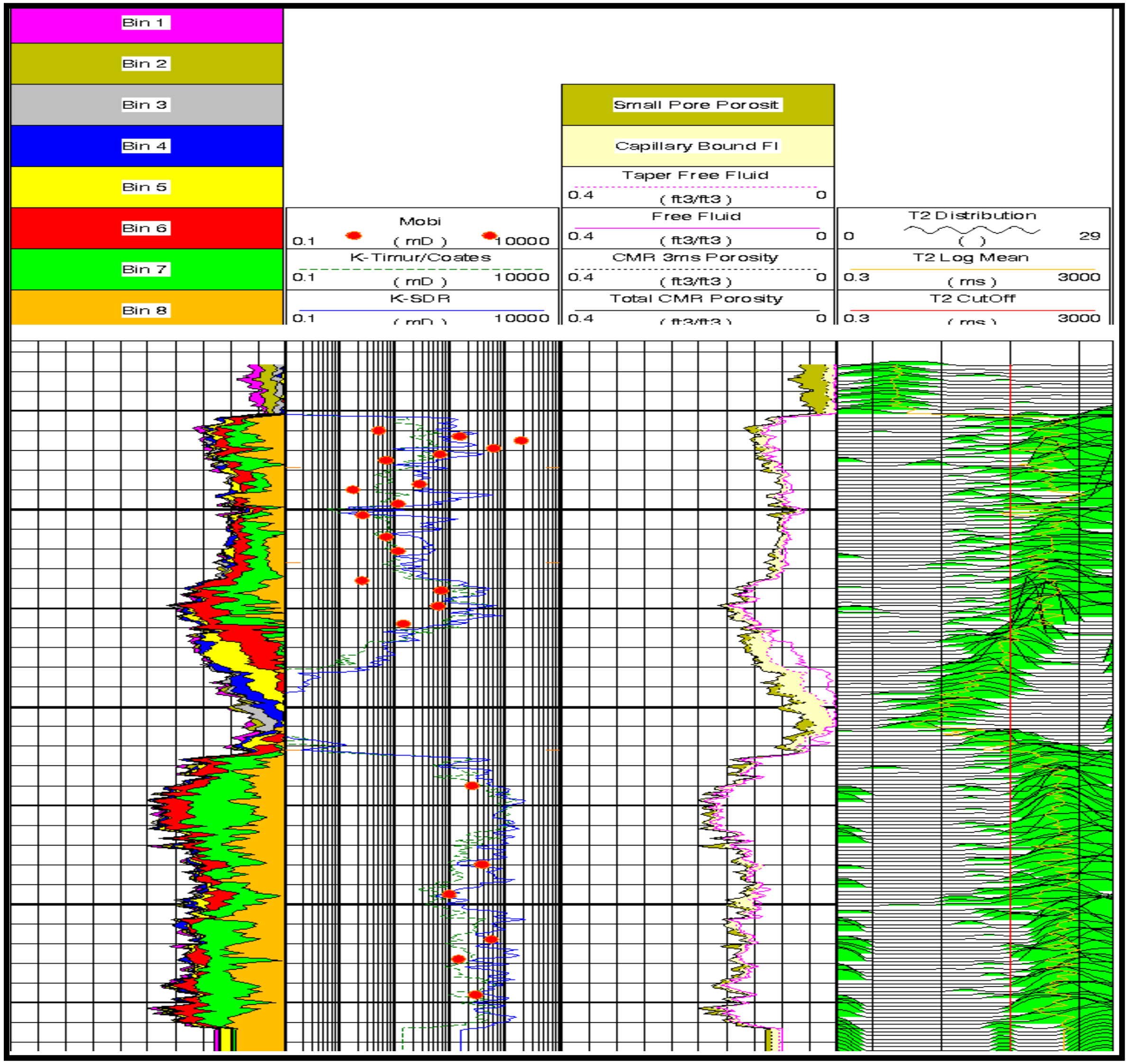
T2 Distributions



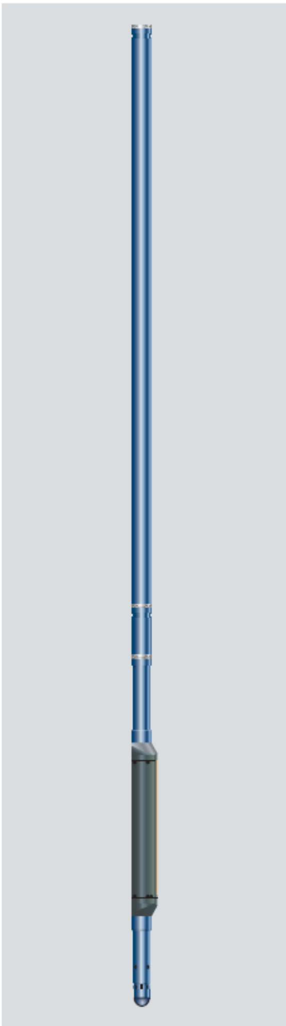
CMR Cross Sectional View



NMR Log Example



Nuclear Magnetic Resonance Logging
Combinable Magnetic Resonance Tool



Measurement Specifications

	CMR-Plus Tool
Output	Transverse relaxation time (T_2) distribution, total porosity, free- and bound-fluid volumes, permeability determined with Schlumberger-Doll Research (SDR) and Timur-Coates equations, capillary bound porosity, small-pore bound porosity, quality control curves and flags MRF Magnetic Resonance Fluid station log: Saturation; oil, gas, and water volumes; oil viscosity; water and oil T_2 distributions; hydrocarbon-corrected permeability; oil and water log-mean T_2 distributions
Logging speed	Bound-fluid mode: 3,600 ft/h [1,097 m/h] Short time constant for the polarizing process (T_1) environment: 2,400 ft/h [731 m/h] Long T_1 environment: 800 ft/h [244 m/h]
Range of measurement	Porosity: 0 to 100 pu Minimum echo spacing: 200 us T_2 distribution: 0.3 ms to 3.0 s Nominal raw signal-to-noise ratio: 32 dB
Vertical resolution	Static: 6-in [15.24-cm] measurement aperture Dynamic (high-resolution mode): 9-in [22.86-cm], three-level averaging Dynamic (standard mode): 18-in [45.72-cm] vertical resolution, three-level averaging Dynamic (fast mode): 30-in [76.20-cm] vertical resolution, three-level averaging
Accuracy	Total CMR porosity standard deviation: ±1.0 pu at 75 degF [24 degC], three-level averaging CMR free-fluid porosity standard deviation: ±0.5 pu at 75 degF [24 degC], three-level averaging
Depth of investigation	Blind zone (2.5% point): 0.50 in [1.27 cm] Median (50% point): 1.12 in [2.84 cm] Maximum (95% point): 1.50 in [3.81 cm]
Mud type or weight limitations	None
Combinability	Combinable with most tools
Special applications	MRF station logging

Mechanical Specifications

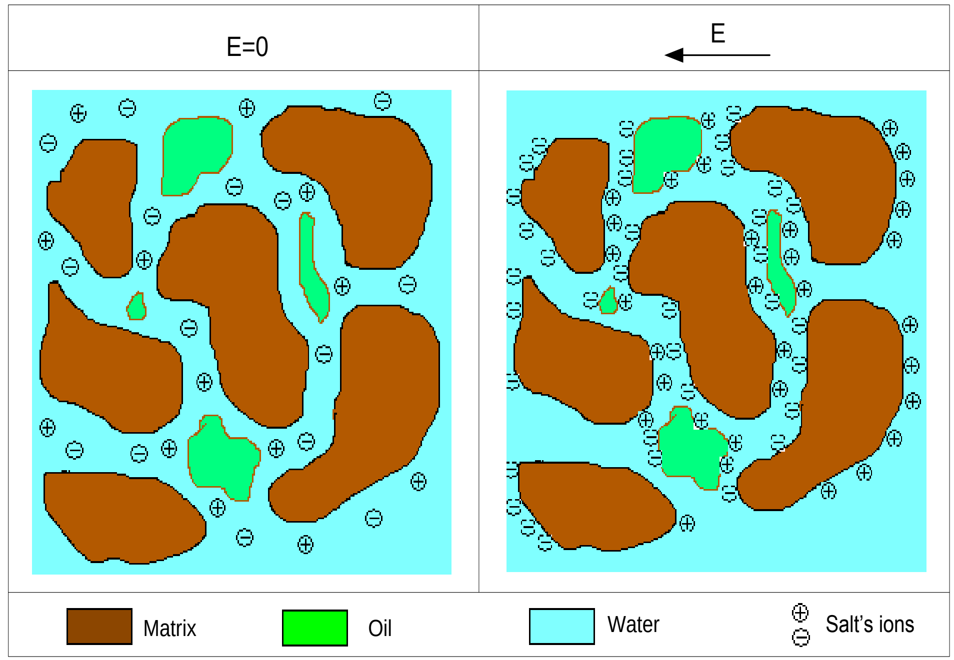
	CMR-Plus Tool
Temperature rating	350 degF [177 degC]
Pressure rating	20,000 psi [138 MPa] High-pressure version: 25,000 psi [172 MPa]
Borehole size—min.	Without integral bow spring: 5⅞ in [14.92 cm] With integral bow spring: 7⅞ in [20.00 cm]
Borehole size—max.	No limit, but must be eccentered
Outside diameter	Without bow spring: 5.3 in [13.46 cm] With bow spring: 6.6 in [16.76 cm]
Length	15.6 ft [4.75 m]
Weight	Without bow spring: 374 lbm [170 kg] With bow spring: 413 lbm [187 kg]
Tension	50,000 lbf [222,410 N]
Compression	50,000 lbf [222,410 N]

Physics – Dielectric Permittivity

Permittivity is:

a physical quantity that describes how an electric field affects, and is affected by a dielectric medium,

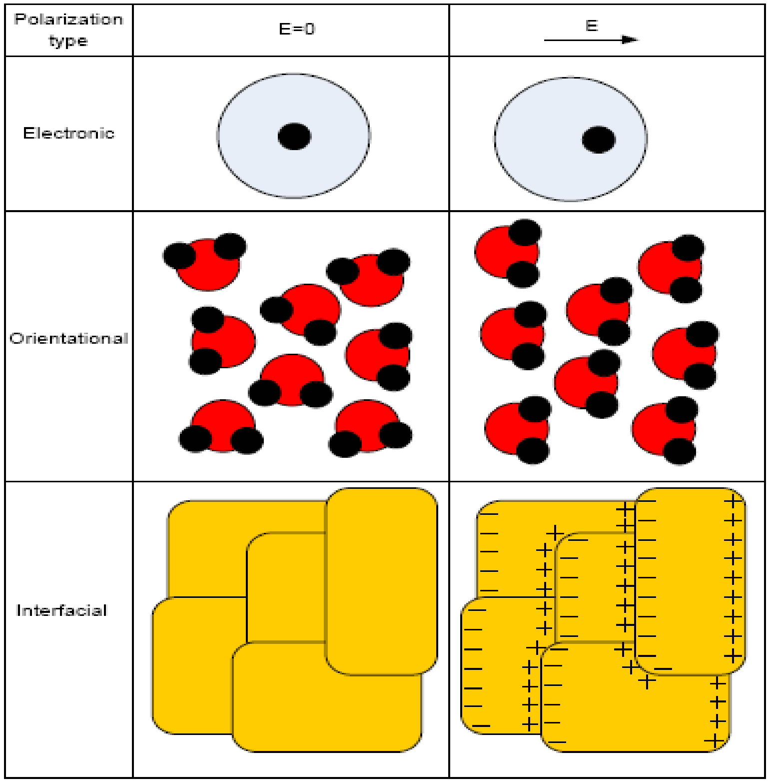
and is determined by the ability of a material to polarize in response to the field,

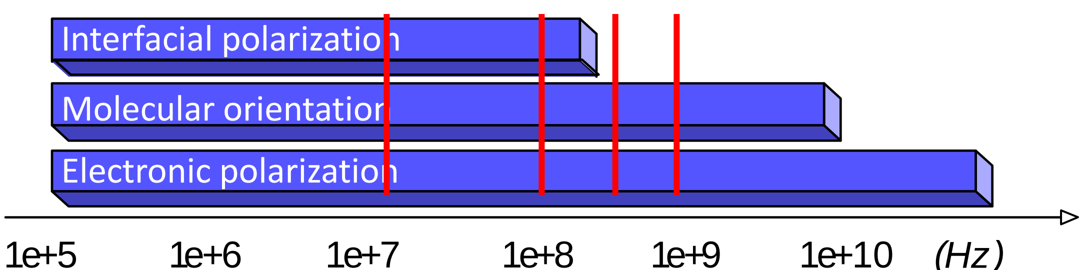


and thereby reduce the total electric field inside the material. Thus, permittivity relates to a material's ability to transmit (or "permit") an electric field.

Dielectric Polarization

Mechanism → Medium Characteristic





- Oil, Rock $\varepsilon_r \sim 2, \; 5 - 9$
- Water $\varepsilon_r \sim 50 - 80$

  Hence, we can discriminate water from hydrocarbons, whatever its salinity
- Textural Effect ?

Dielectric as function of frequency

- Pore fluid analysis
- Formation matrix analysis

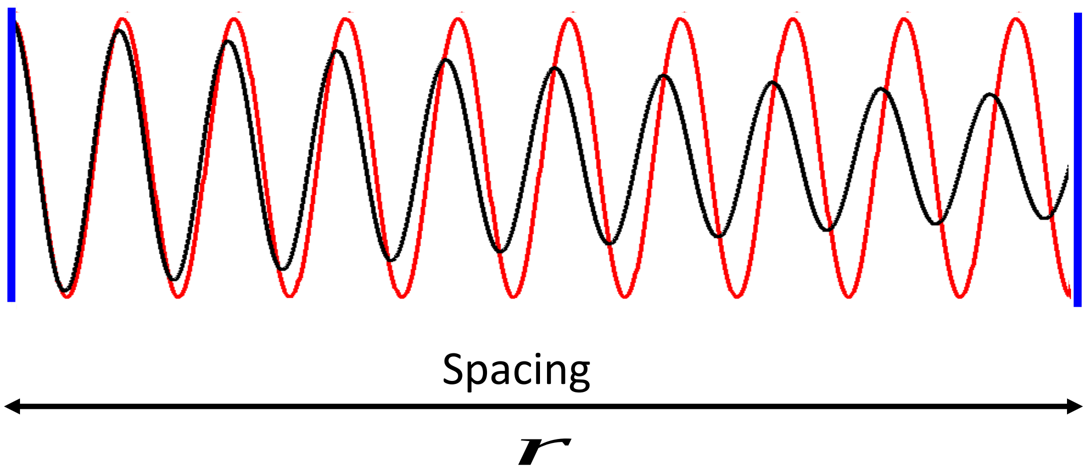
Principle of Dielectric Measurement

Electromagnetic → Physical properties → Reservoir parameters

Transmitter

frequency ω

- Vacuum
- Medium



Receiver

$$V^* = f(\omega, \varepsilon, \sigma, r)$$
$$= Ae^{i\phi}$$

- Dielectric dispersion is the variation of permittivity as a function of frequency

Amplitude A, Phase ϕ $\xrightarrow{f^{-1}}$ ε Permittivity, σ Conductivity

- The Dielectric scanner toc[...]e dielectric dispersion of the formation

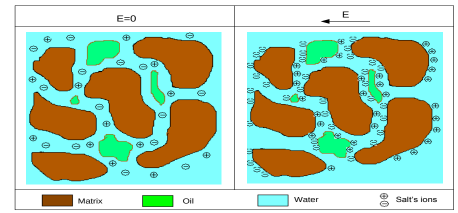
$$\varepsilon^* = \varepsilon_r + i\frac{\sigma}{\omega\varepsilon_0}$$

Pore Fluid Analysis : CRIM

Electromagnetic → Physical properties → Reservoir parameters

Measurement of complex permittivity : relative permittivity & conductivity

$$\varepsilon^* = \varepsilon_r + i\frac{\sigma}{\omega\varepsilon_0}$$



At the highest frequency of the tool, the **C**omplex **R**efractive **I**ndex **M**odel is an accurate mixing law

$$\sqrt{\varepsilon^*} = (1-\phi_T)\sqrt{\varepsilon_m} + \phi_T\left(S_w\sqrt{\varepsilon_w^*} + (1-S_w)\sqrt{\varepsilon_{oil}}\right)$$

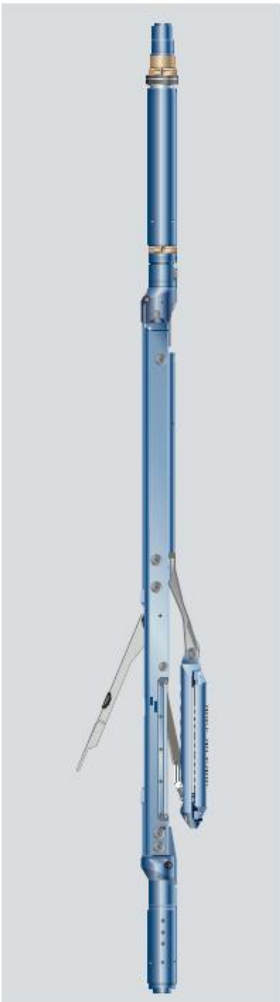
With $\varepsilon_w^* = fct(ppk, T, P)$ water dielectric model

ϕ_T & ε_m

Measured permittivity ε
Measured conductivity σ
→
S_w water saturation
σ_w water conductivity

φρομ Ν Σελεζνεω ΣΠΩΛΑ 2004

Dielectric Dispersion Logging
Dielectric Scanner



Measurement Specifications	
	Dielectric Scanner Tool
Output	Relative dielectric permittivity and conductivity at four frequencies
Logging speed	3,600 ft/h [1,097 m/h]
Range of measurement at highest frequency	Permittivity: 1 to 100 Conductivity: 0.1 to 3,000 mS
Vertical resolution‡	1 in [2.5 cm]
Accuracy at highest frequency	Corresponding to 0.002-ft^3/ft^3 [0.002-m^3/m^3] water-filled porosity Permittivity: ±1% or ±0.1 Conductivity: ±1% or ±5 mS
Depth of investigation	To 4 in [10 cm]
Mud type or weight limitations	None
Combinability	Conveyance on wireline, TLC* tough logging conditions system, or tractor
Special applications	Articulated pad for rugose boreholes

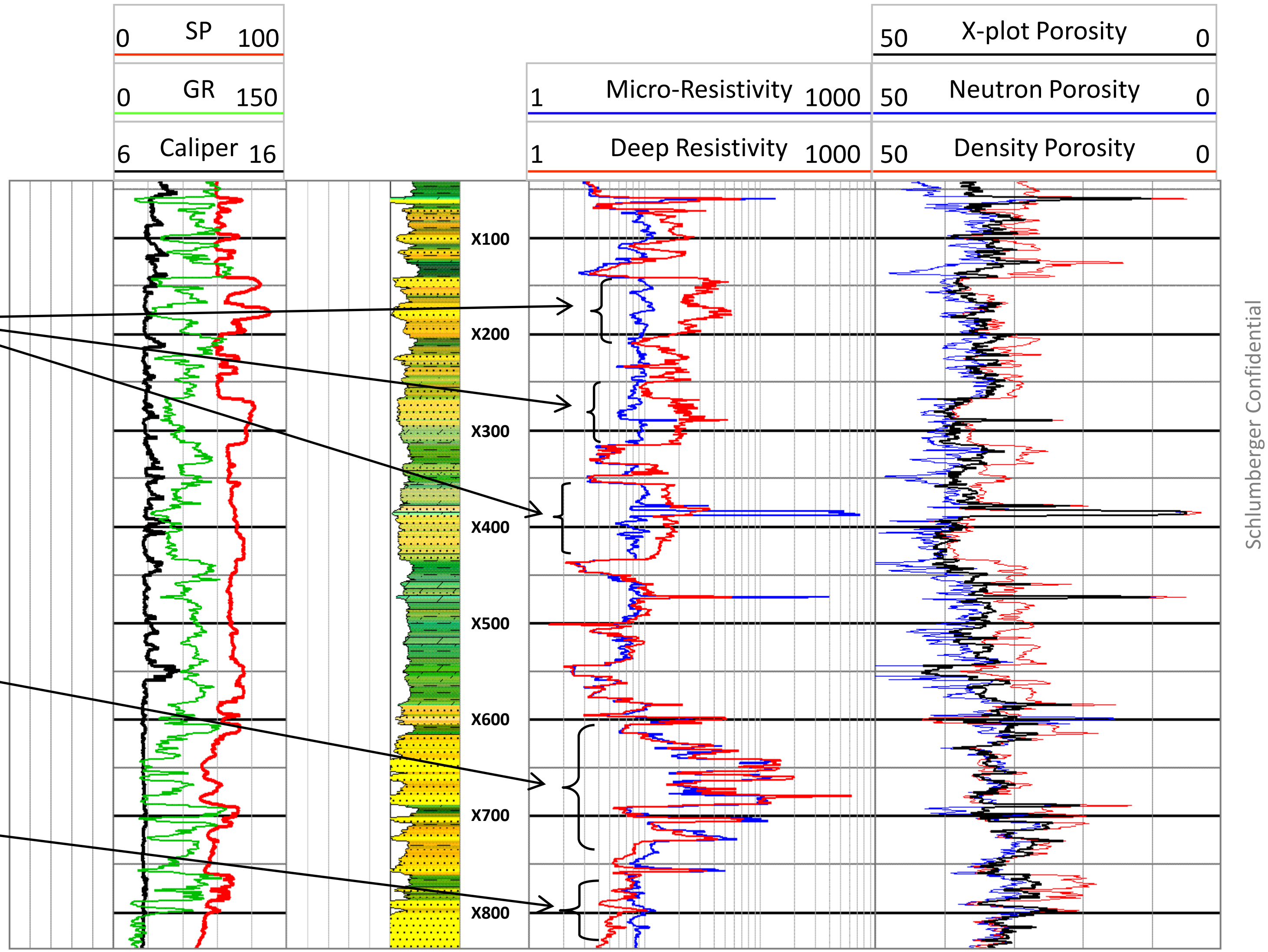
‡1-in resolution depending on frequency

Mechanical Specifications	
	Dielectric Scanner Tool
Temperature rating	302 degF [150 degC]
Pressure rating	15,000 psi [103 MPa]
Outside diameter	4.77 in [12.12 cm]
Borehole size—min.	5.5 in [13.97 cm]
Borehole size—max.	22.0 in [55.88 cm]
Min. restriction	5.25 in [13.34 cm]
Length	11.27 ft [3.44 m]
Weight	262 lbm [119 kg]
Tension	50,000 lbf [222,411 N]
Compression‡	4,400 lbf [19,572 N]

‡8,000 lbf [35,586 N] with TLC stiffener kit

Variable Formation Water Salinity

Standard logs



Moved Oil ?

High deep resistivity and high porosity

Invasion from shallow resitivity

Heavy oil

Water zone

Variable Formation Water Salinity

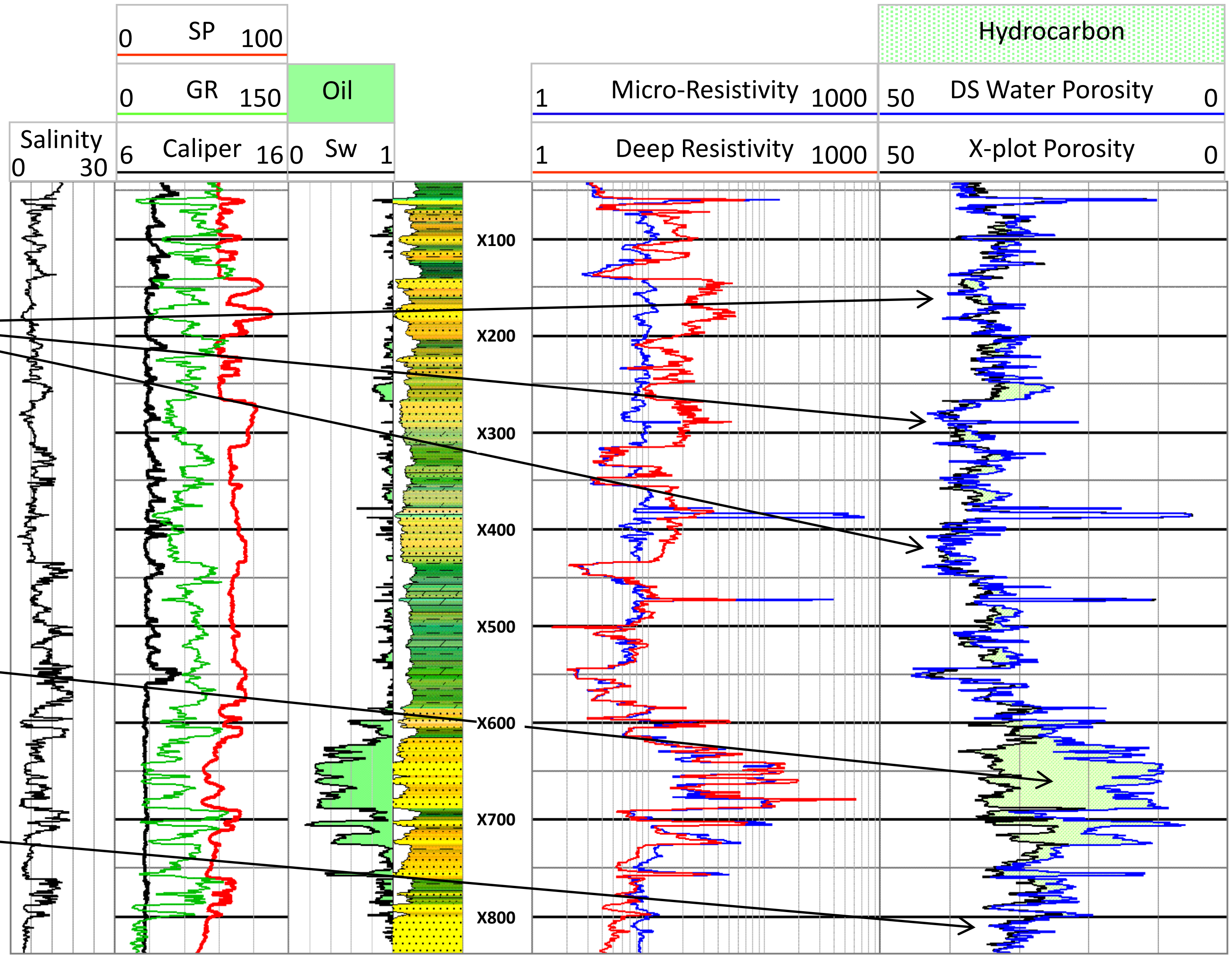
Dielectric-Scanner real time answer

Fresh Water

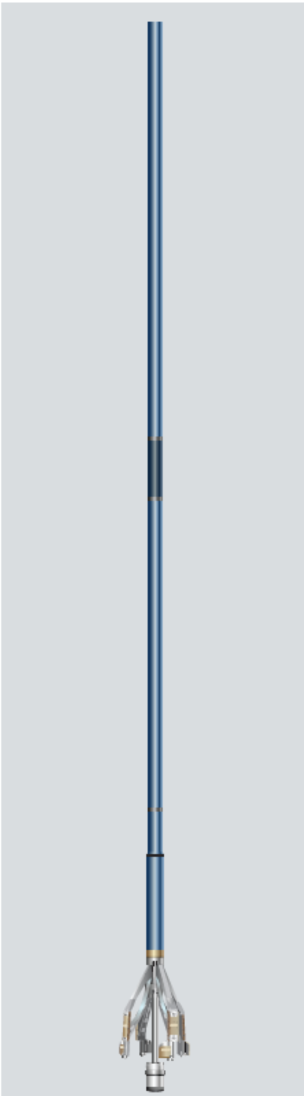
Dielectric water filled porosity overlays with total porosity

Heavy oil

Water zone



Geological Imaging Measurements
Formation MicroImager

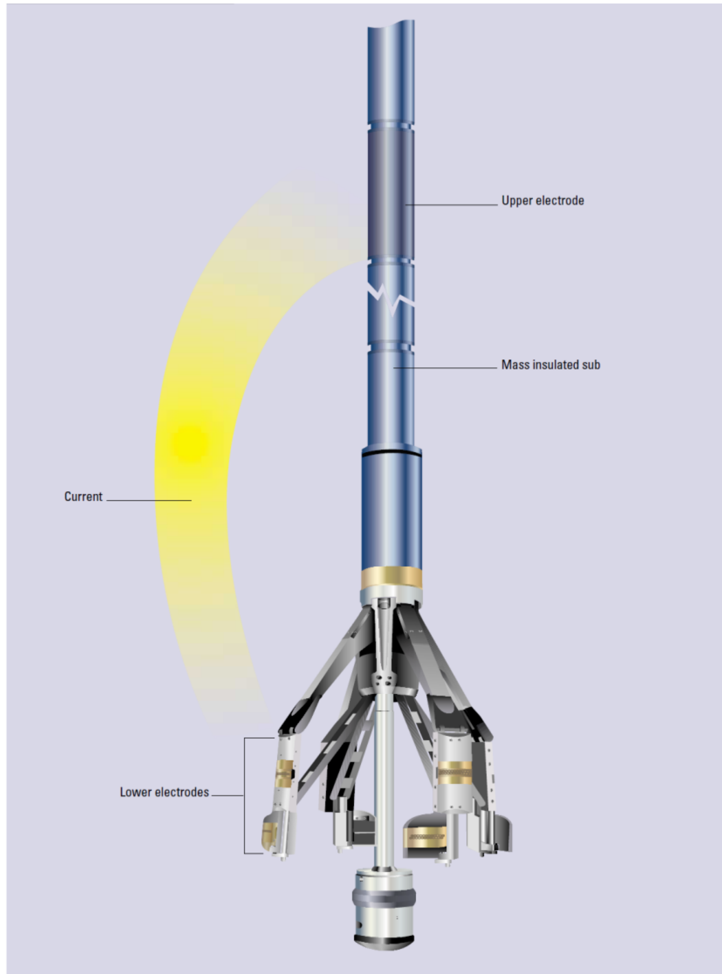


Measurement Specifications	
	FMI Tool
Output	Formation dip, borehole images
Logging speed	Image mode: 1,800 ft/h [549 m/h] Dipmeter mode: 3,600 ft/h [1,097 m/h]
Range of measurement	Sampling rate: 0.1 in [0.25 cm] Borehole coverage: 80% in 8-in [20.32-cm] borehole
Vertical resolution	Spatial resolution: 0.2 in [0.51 cm] Vertical resolution: 0.2 in [0.51 cm]
Accuracy	Caliper: ±0.2 in [±0.51 cm] Deviation: ±0.2° Azimuth: ±2°
Depth of investigation	1 in [2.54 cm]
Mud type or weight limitations	Water-base mud (max. mud resistivity = 50 ohm.m)
Combinability	Bottom-only tool, combinable with most tools
Special applications	Horizontal wells

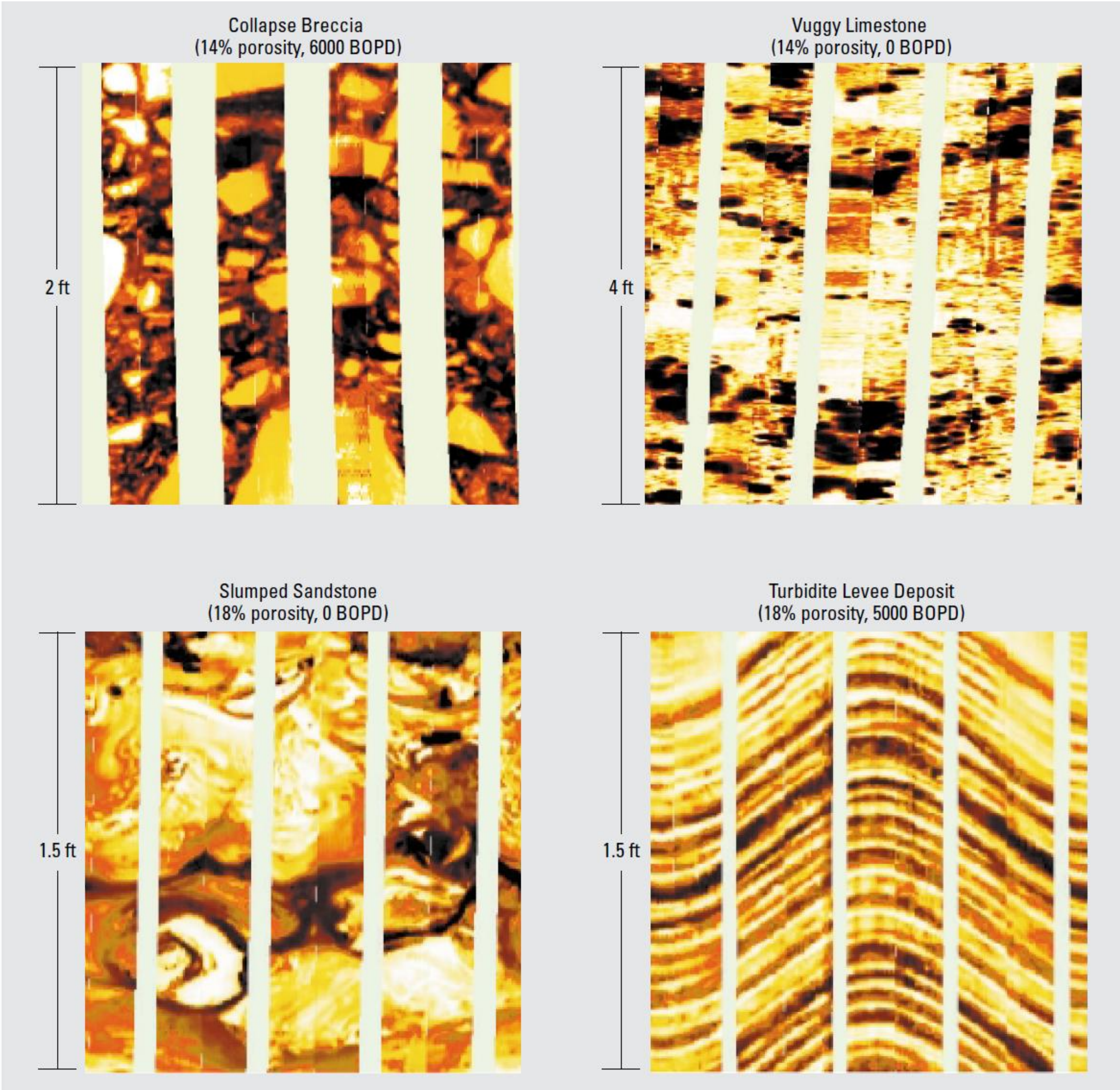
Mechanical Specifications	
	FMI Tool
Maximum temperature	350 degF [177 degC]
Maximum pressure	20,000 psi [138 MPa]
Borehole size—min.†	6¼ in [15.87 cm]
Borehole size—max.	21 in [53.34 cm]
Outside diameter	5 in [12.70 cm]
Length	24.42 ft [7.44 m]
Weight	433.7 lbm [197 kg]
Tension	12,000 lbf [53,380 N]
Compression	8,000 lbf [35,580 N]

† 5⅞ in [14.92 cm] in good hole conditions using a kit

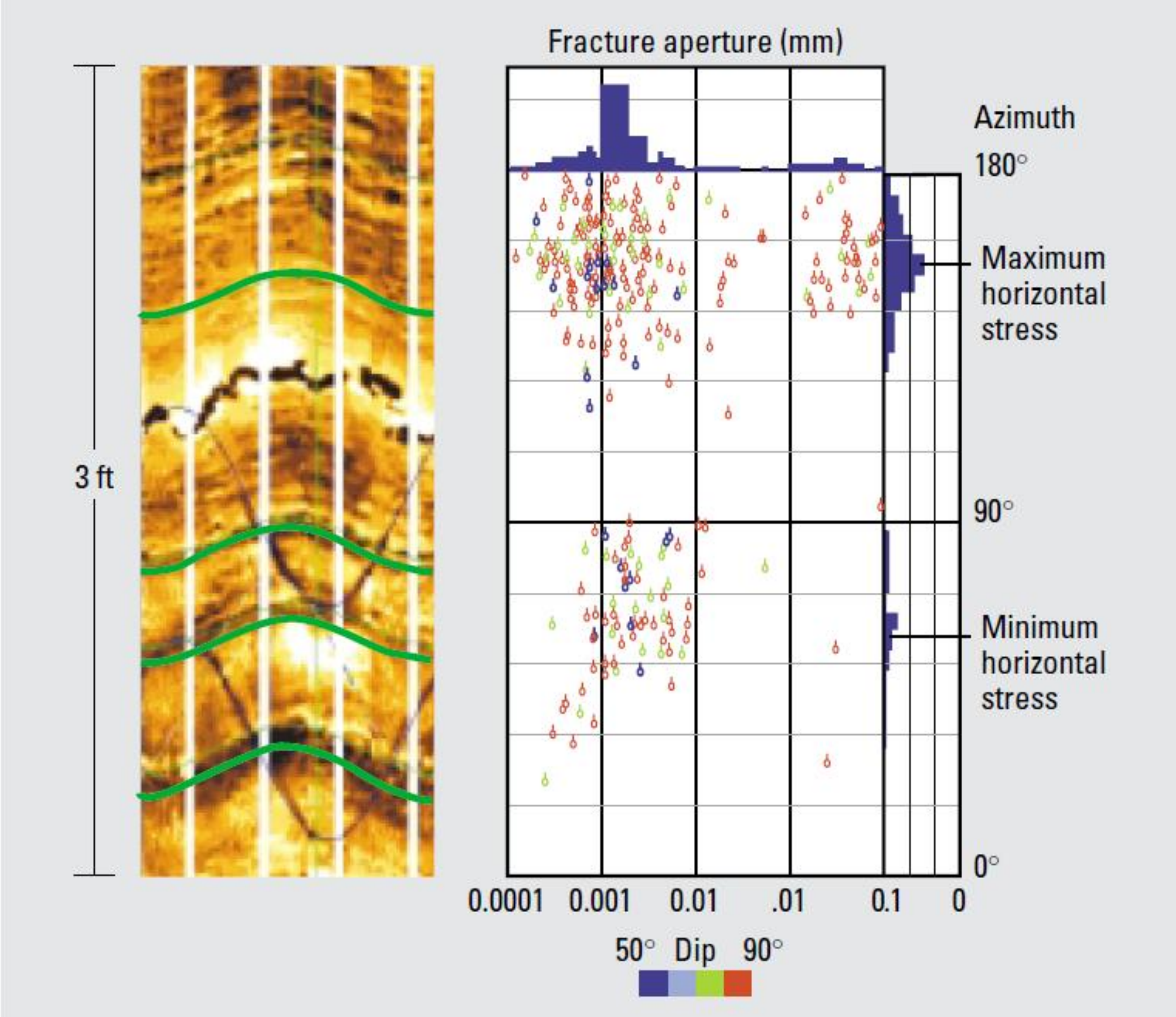
FMI Current Path



FMI Structure Differentiation

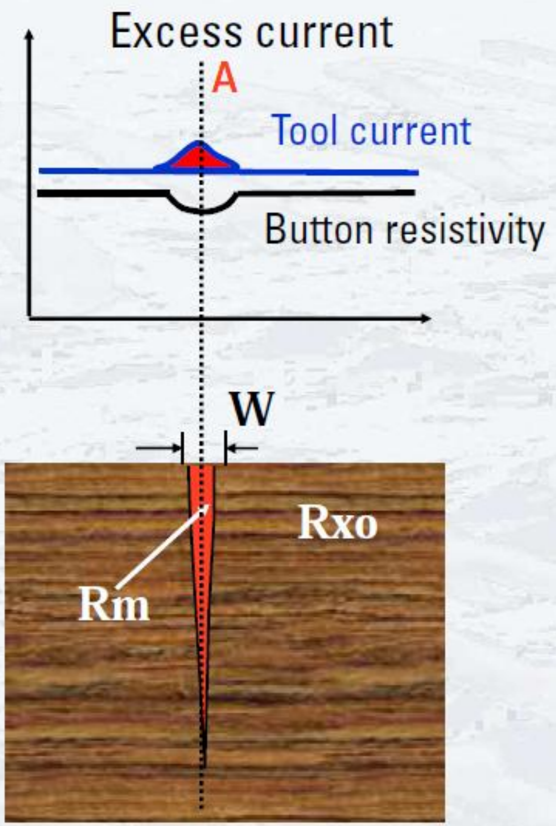


FMI Fracture Aperature



Fracture Aperature

Empirical formula from Philippe Souhaité et all:



$$W = c.A.R_m^{\,b}.R_{xo}^{\,1-b}$$

Assumptions
- infinite fracture
- completely open fracture
- conductive material filling the fracture is drilling mud

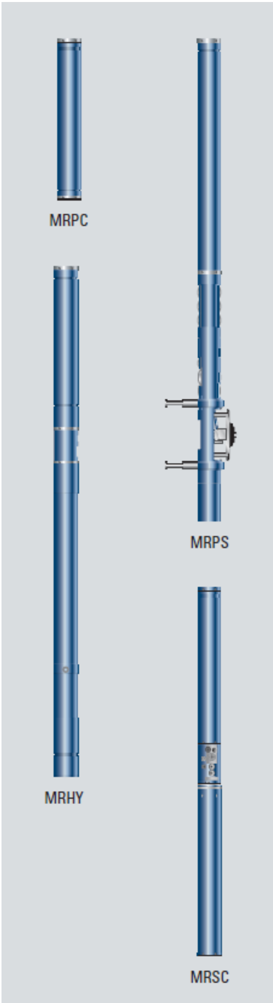
Limitations
- same response if fracture sealed with conductive material such as pyrite or clay
- aperture calculation affected by fluids (hydrocarbon bearing zones vs water bearing zones)

Borehole Seismic Measurements

Measurement Specifications	
	VSI Tool
Output	Seismic waveform produced by acoustic reflections from bed boundaries
Logging speed	Stationary Seismic waveform recording: 0.5-, 1-, 2-, or 4-ms output sampling rate
Array capability	Up to 40 shuttles
Sensor package	
Length	11.4 in [28.96 cm]
Weight	6.4 lbm [2.9 kg]
Sensor	Geophone Accelerometer (GAC-D)
Sensitivity	>0.5 V/g ± 5%
Sensor natural frequency	25 Hz Flat bandwidth in acceleration: 2 to 200 Hz
Dynamic range	>105 dB at 36-dB gain
Distortion	<–90 dB
Digitization	24-bit analog-to-digital converter
Combinability	Bottom-only combinable
Special applications	Conveyance on wireline, TLC system, tractor, or through drillpipe

Mechanical Specifications	
	VSI Tool
Temperature rating	350 degF [177 degC]
Pressure rating	Standard: 20,000 psi [138 MPa] High pressure: 25,000 psi [172 MPa]
Borehole size—min.	3 in [7.62 cm]
Borehole size—max.	22 in [55.88 cm]
Outside diameter	Standard: 3⅜ in [8.57 cm] Slim: 2½ in [6.35 cm]
Length	Up to 1,040 ft [317 m] for 20 shuttles
Weight	Up to 2,200 lbm [998 kg]
Tension	18,000 lbf [80,070 N]
Compression	Standard: 5,000 lbf [22,240 N] With stiffener: 10,000 lbf [44,480N]
Coupling	
Anchoring force	246 lbf [1,170 N] in 3-in [7.62-cm] hole 214 lbf [915 N] in 6-in [15.24-cm] hole 255 lbf [1,130 N] in 12¼-in [31.75-cm] hole 160 lbf [951 N] in 17-in [43.18-cm] hole
Sensor package coupling force	64 lbf [285 N]
Coupling force/sensor weight ratio	10:1

Reservoir Formation Testing and Sampling
Modular Formation Dynamics Tester



Standard MDT Tool Measurement Specifications

	Accuracy	Resolution	Range
Logging speed	Stationary	Stationary	Stationary
Strain gauge[†]	±10 psi [±68,947 Pa] ±20 psi [±137,895 Pa]	0.1 psi [689 Pa] 0.2 psi [1,379 Pa]	0 to 10,000 psi [0 to 69 MPa] 0 to 20,000 psi [0 to 138 MPa]
CQG gauge[‡]	±(2 psi [13,789 Pa] + 0.01% of reading) ±(4.0 psi [27,579 Pa] + 0.012% of reading)[§]	0.008 psi [55 Pa] at 1.3-s gate time 0.008 psi [55 Pa] at 1.3-s gate time	750 to 15,000 psi [5 to 103 MPa] 0 to 25,000 psi [0 to 172 MPa]
Resistivity	±5% of reading	0.001 ohm.m	0.01 to 20 ohm.m
Flowline temperature	±1.0 degF [±0.5 degC]	1.0 degF [0.5 degC]	–67 to 392 degF [–55 to 200 degC]

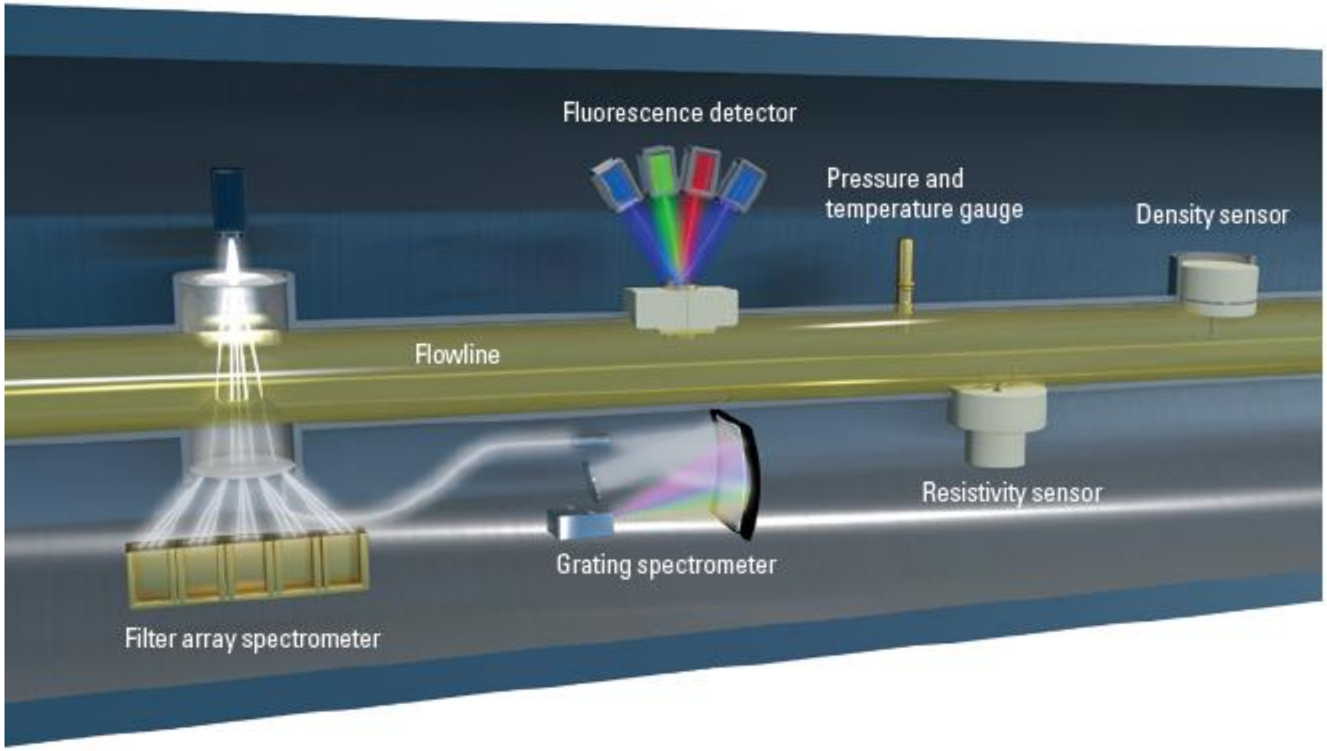
[†] 30,000-psi [207-MPa] strain gauge is available on request.
[‡] There are several versions of the CQG gauge. The CQG-C and CQG-G gauges are rated to 15,000 psi [103 MPa] and 350 degF [177 degC]. The HCQG-A gauge is rated to 25,000 psi [172 MPa] and 350 degF. A 30,000-psi [207-MPa] quartz gauge is available on request.
[§] The 2- and 4-psi accuracy claims include calibration fitting error, hysteresis, repeatability, and some allowance for sensor aging; the corresponding percentages of the pressure readings account for the incertitude of the calibration equipment.

Basic MDT Modules Mechanical Specifications

	MRPC	MRHY	MRSC	MRPS
Temperature rating	392 degF [200 degC]	392 degF [200 degC]	392 degF [200 degC]	392 degF [200 degC][†]
Pressure rating	20,000 psi [138 MPa]	20,000 psi [138 MPa]	20,000 psi [138 MPa]	20,000 psi [138 MPa][†]
Borehole size—min.	5⅝ in [14.29 cm]	5⅝ in [14.29 cm]	5⅝ in [14.29 cm]	Standard: 5⅝ in [14.29 cm] Large-hole kit: 8½ in [21.59 cm] Super-large-hole kit: 11½ in [29.21 cm]
Borehole size—max.	No limit	No limit	No limit	Standard: 14 in [35.56 cm] Large-hole kit: 19 in [48.26 cm] Super-large-hole kit: 22 in [55.88 cm]
Outside diameter	4.75 in [12.07 cm]	4.75 in [12.07 cm]	4.75 in [12.07 cm]	Standard: 4.75 in [12.07 cm] Large-hole kit: 7.5 in [19.05 cm] Super-large-hole kit: 10.5 in
Length	4.98 ft [1.52 m]	8.42 ft [2.57 m]	8.04 ft [2.45 m]	6.25 ft [1.91 m]
Weight	160 lbm [73 kg]	275 lbm [125 kg]	225 lbm [102 kg]	200 lbm [91 kg]
Tension[‡]	160,000 lbf [711,710 N]	160,000 lbf [711,710 N]	160,000 lbf [711,710 N]	160,000 lbf [711,710 N]
Compression[‡]	85,000 lbf [378,100 N]	85,000 lbf [378,100 N]	85,000 lbf [378,100 N]	85,000 lbf [378,100 N]
H_2S service	Yes	Yes	Yes	Yes

[†] Excluding the quartz gauge, the pressure and temperature ratings of the MRPS are 20,000 psi [138 MPa] and 293 degF [200 degC], respectively. These ratings can reduce the dependence on using a quartz gauge, of which there are several versions with various pressure and temperature ratings.
[‡] At 15,000 psi [103 MPa] and 320 degF [160 degC]. These ratings apply to all MDT modules except the Dual-Packer Module (MRPA). The compressive load is a function of temperature and pressure.

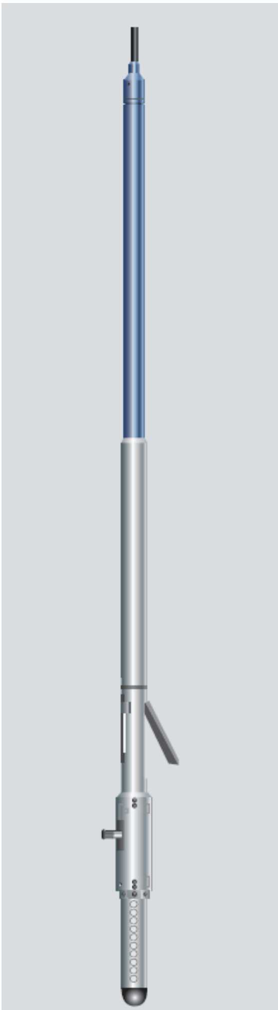
Reservoir Formation Testing and Sampling
InSitu Fluid Analysis



InSitu Fluid Analyzer service integrates multiple InSitu Family reservoir fluid measurements and sensors.

Measurement Specifications	
	InSitu Fluid Analyzer System
Output	Hydrocarbon composition, GOR, live-oil density, CO_2, pH of water, reservoir fluid color, free-gas detection, downhole fluorescence, flowline pressure and temperature, resistivity, OBM contamination
Logging speed	Stationary

Reservoir Formation Testing and Sampling
Mechanical Sidewall Coring Tool



Measurement Specifications

	MSCT
Output	Sidewall core samples†
Logging speed	Stationary Coring time (avg): 3 to 5 min per core
Range of measurement	Core size: 2 in [50.8 mm] long × 0.92 in [23.4 mm] diameter
Depth of core sample	Core length: 1.5 or 1.75 in [38.1 or 44.4 mm]
Mud type or weight limitations	None
Special applications	

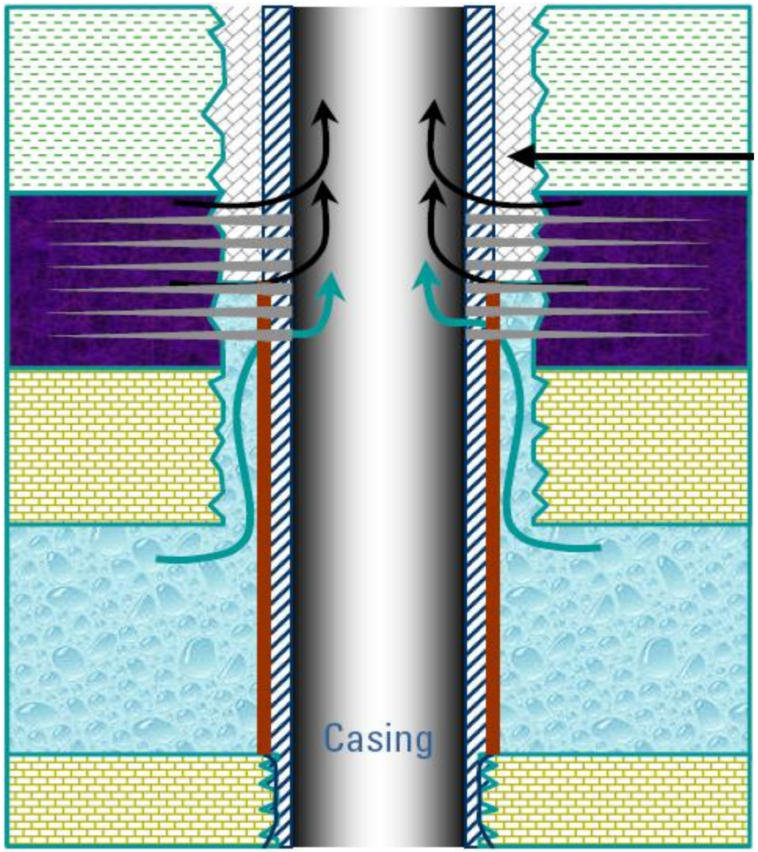
† The MCFU-AA is used for 50 cores per descent and the MCCU is used for 20 cores per descent.

Mechanical Specifications

	MSCT
Temperature rating	350 degF [177 degC]†
Pressure rating	Standard: 20,000 psi [138 MPa] High pressure: 25,000 psi [172 MPa]
Borehole size—min.	6¼ in [15.87 cm]
Borehole size—max.	19 in [48.26 cm]
Outside diameter	5⅜ in [13.65 cm]‡
Length	31.29 ft [9.54 m]
Weight	750 lbm [340 kg]§
Tension	22,900 lbf [101,860 N]
Compression	12,500 lbf [55,600 N]

† The MSCT-A can be run at 400 degF [204 degC] with a Dewar flask (UDFH-KF). Successful jobs have also been performed at 425 degF [218 degC].
‡ With the standoffs removed, the MSCT can be stripped down to 5 in [12.70 cm] and run in 5⅞-in [14.92-cm] holes.
§ The sonde weighs 580 lbm [263 kg].

CBL-VDL Applications

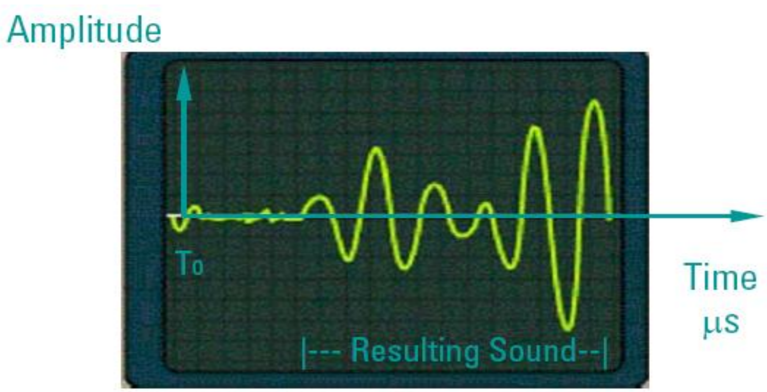


Client Needs

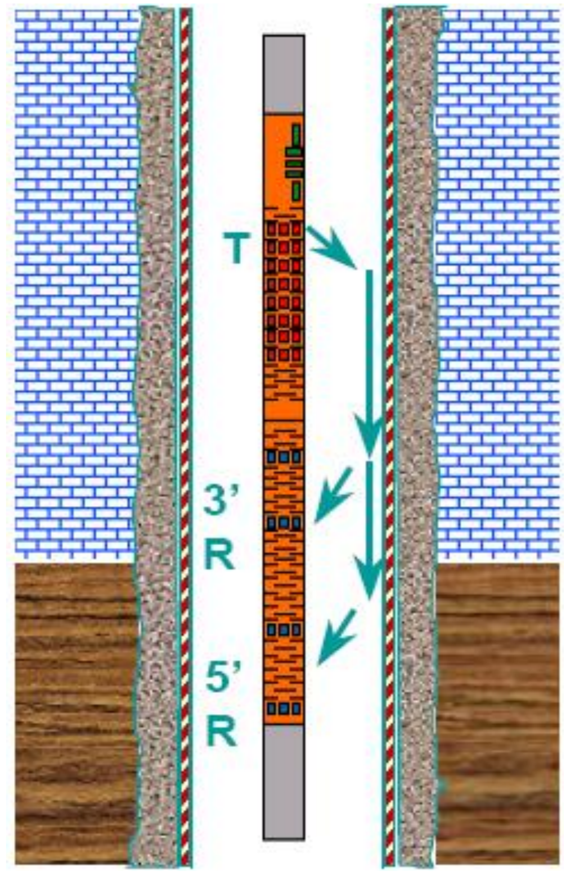
- Check Cement Integrity
- Verify Zone Isolation
- Cement Strength
- Channels?
- Repair?
- Is a Squeeze Possible?
- Where is Top of Cement?

CBL-VDL Sonic Fundamentals

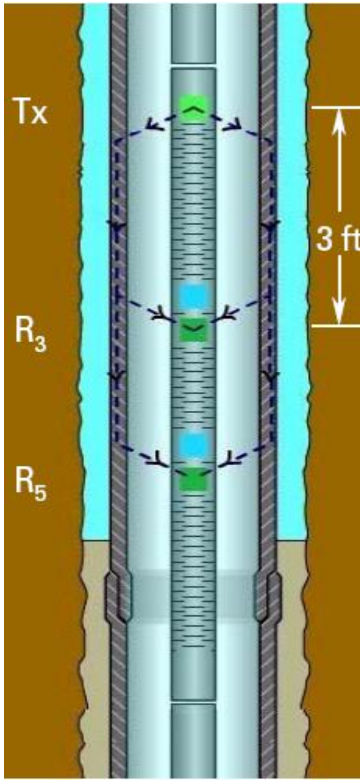
- Transmitter sends Omni directional Pulse
- Compression Wave Reaches Receivers
  - 3 ft Receiver for CBL
  - 5 ft Receiver for VDL
- Tool must be Centralized

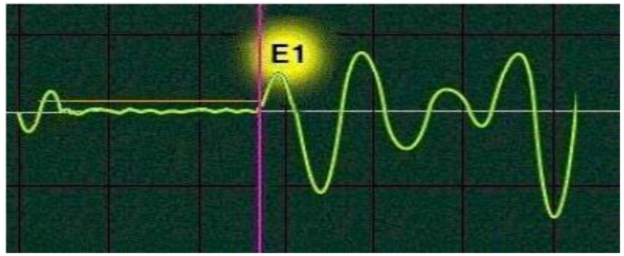


- T0 : Firing Pulse
- Resulting Sound: as recorded at the Receivers



What is the "CBL"

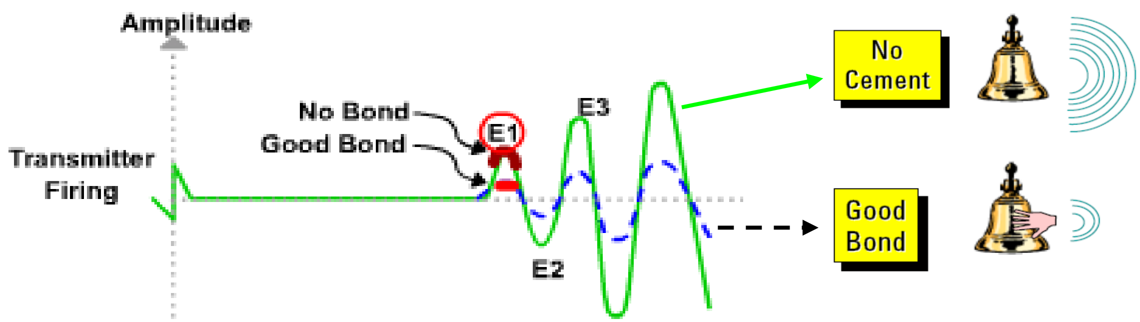




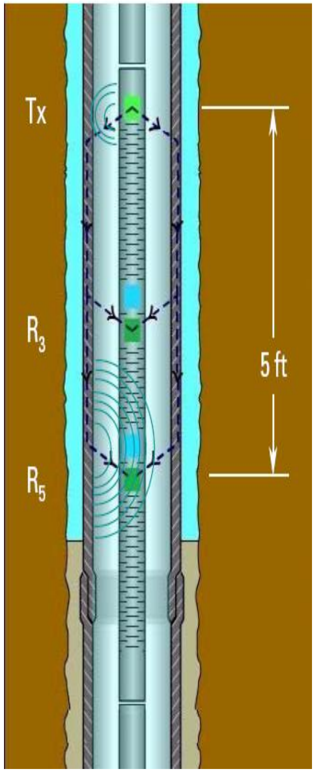
High Amplitude=Poor Bond

Low Amplitude=Good Bond

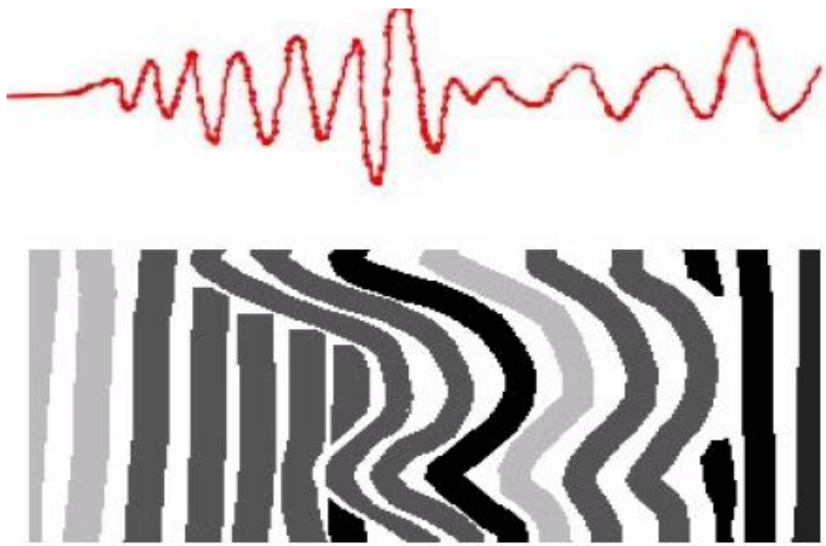
- Like Ringing a Bell
- Amplitude of the First Arrival in mV
- Measured at the 3-ft Receiver
- Function of the Casing-Cement Bond

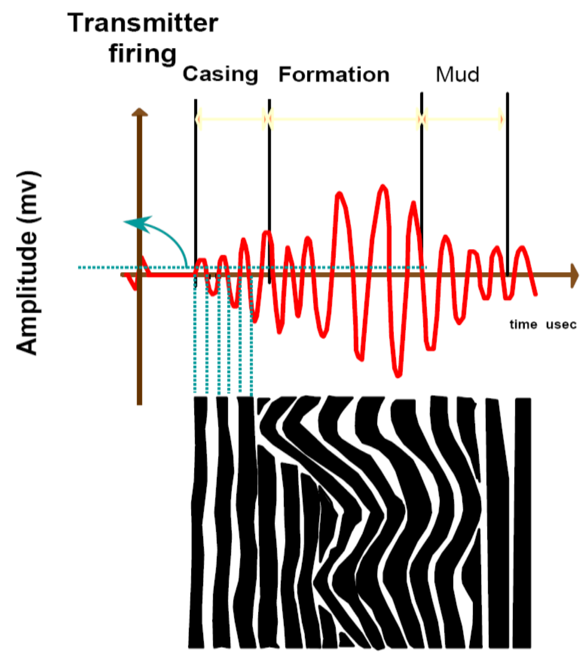


What is the "VDL"

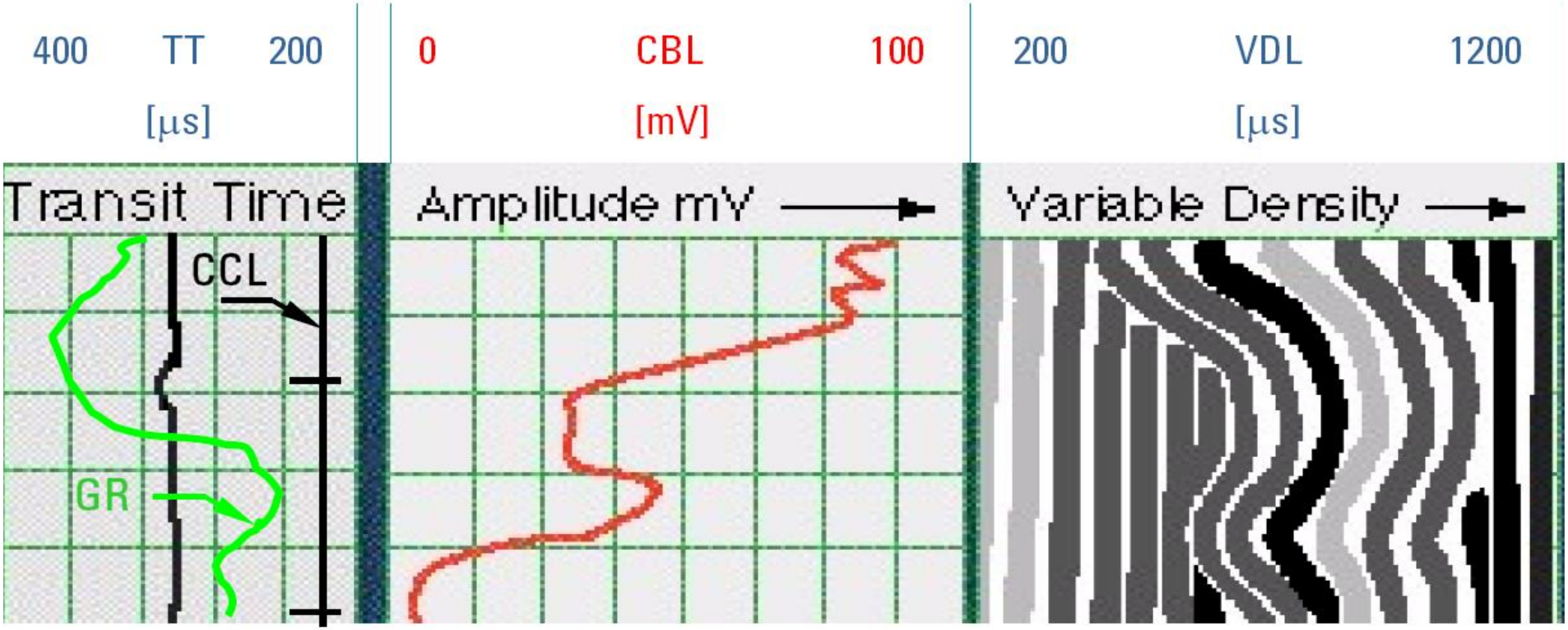


- 5-Ft Receiver Waveform
- Imagine Looking at it from the top
- Dark is High Amplitude
- Allows for Easy Differentiation between Casing and Formation Signals

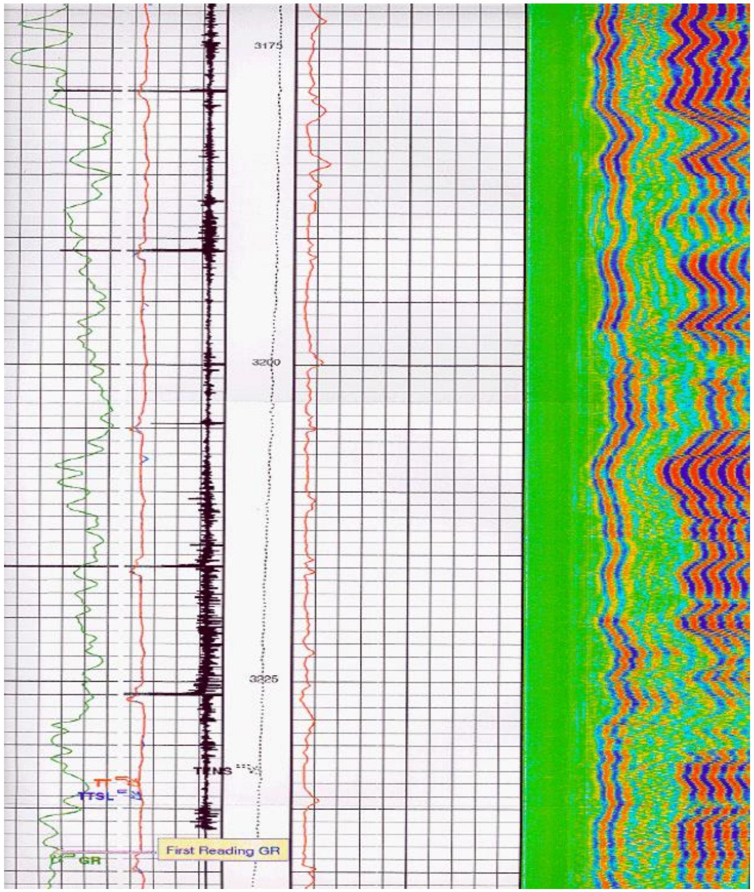


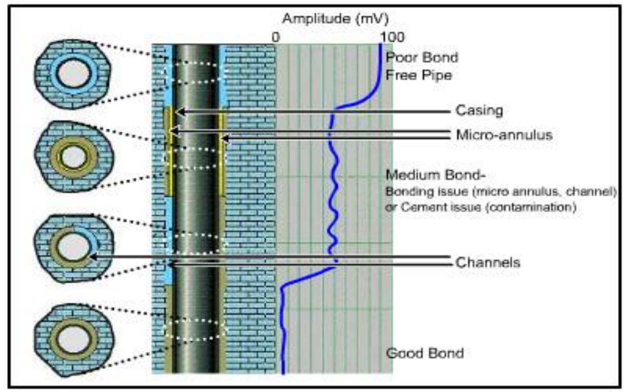


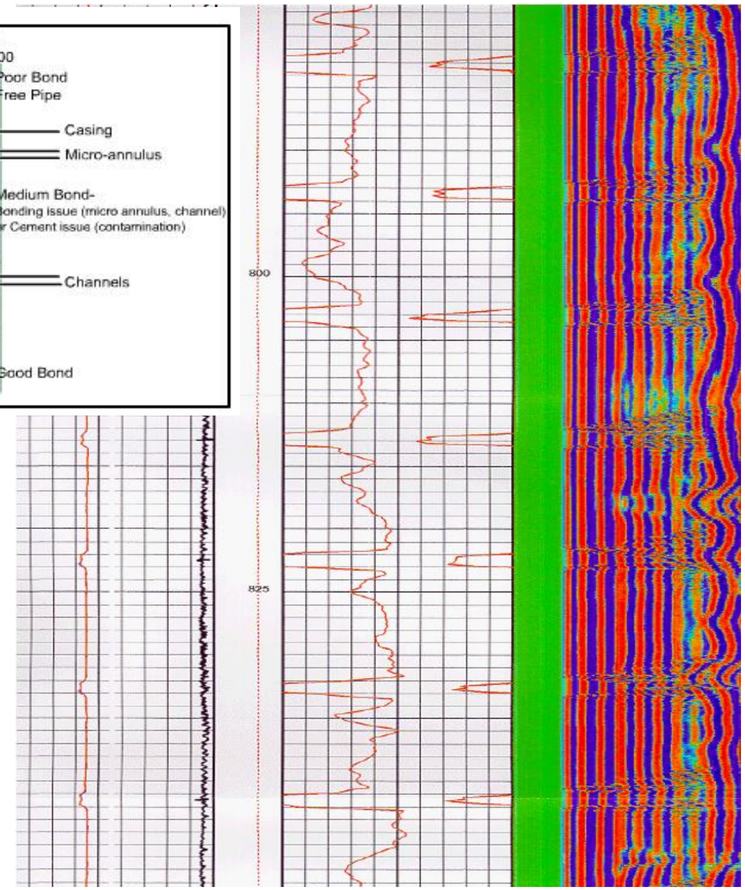
Standard CBL-VDL Log



“Good” and “Bad” Cement Jobs







Qualitative Interpretation

CONDITION	TRANSIT TIME	CBL AMPLITUDE	VDL
Free Pipe	NORMAL	HIGH	Casing Arrivals Usually No Formation Arrivals
Good Bond to Casing & Formation	HIGH / NOISY	LOW	No Casing Arrivals Formation Arrivals
Good Bond to Casing Not to Formation	HIGH CAN BE NOISY	LOW	No Casing Arrivals No Formation Arrivals
Poor Bond to Casing	NORMAL	MEDIUM	Strong Casing Arrivals No Formation Arrivals
Microannulus	NORMAL	MEDIUM	Formation Arrivals Casing Arrivals
Channeling	NORMAL	MEDIUM	Formation Arrivals Casing Arrivals
Fast Formations	LOW	HIGH	Formation Arrivals No Casing Arrivals
Eccentered Tool	LOW	LOW	DEPENDS

Additional Measurements Often Needed

Ultrasonic Imager (USIT)

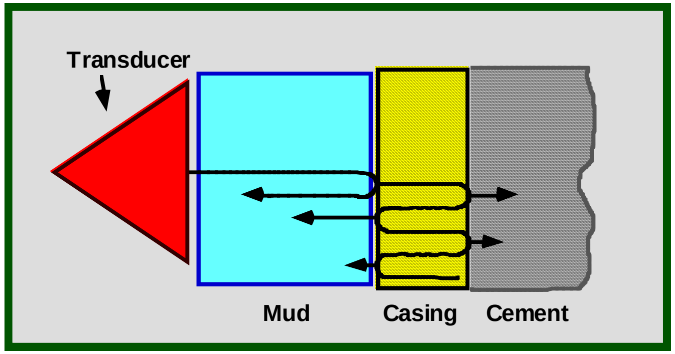
Objective: azimuthal evaluation

Ultrasonic tool operating between 200 and 700 kHz

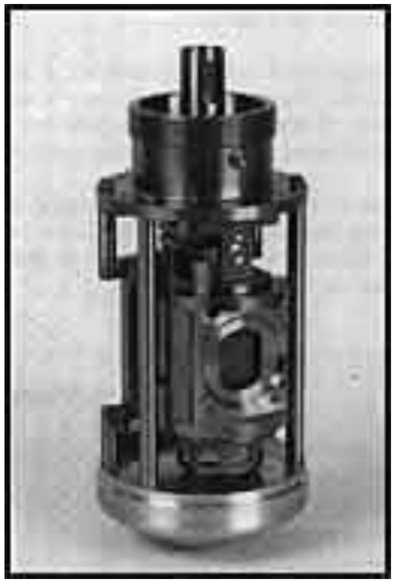
Full casing coverage at using rotating transducer

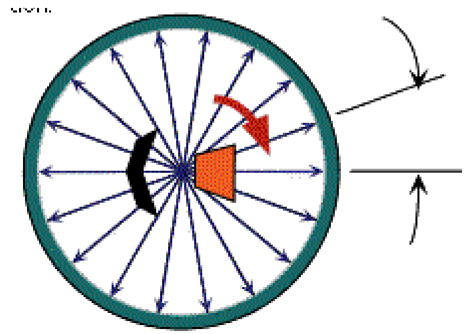
Measurements

- Cement evaluation
- Casing corrosion and wear

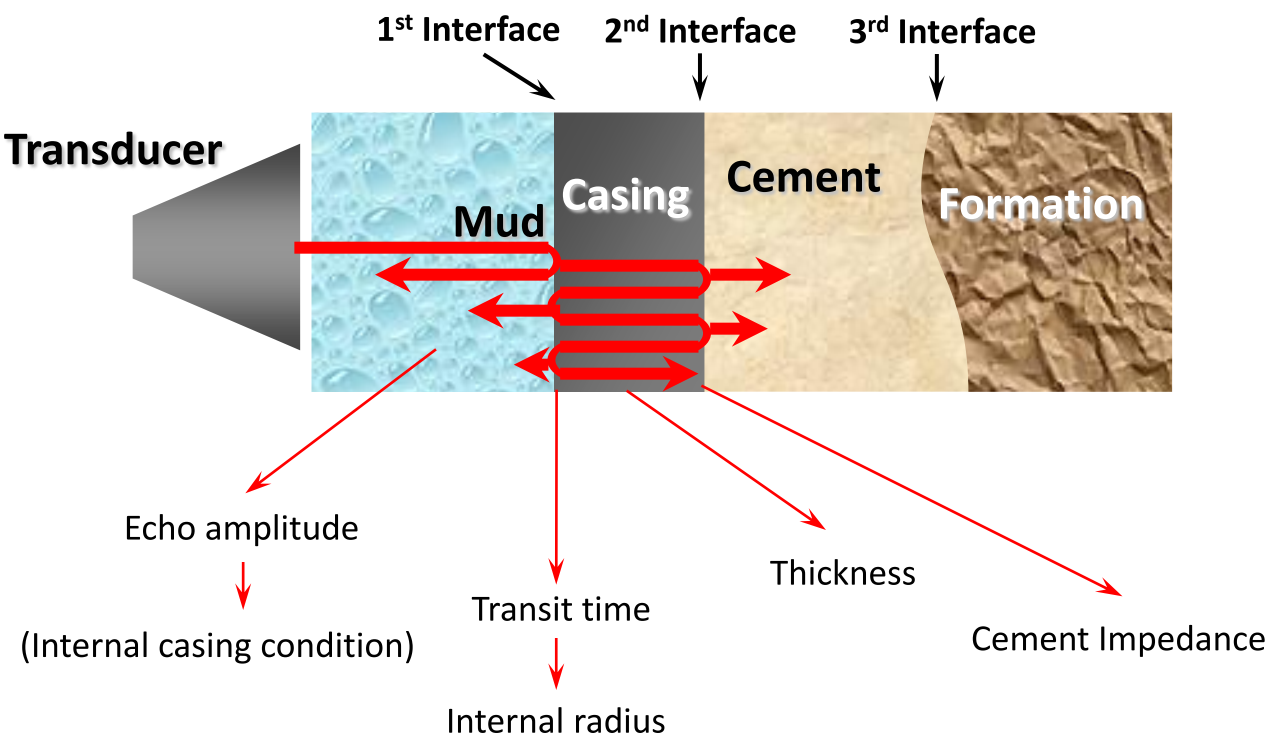


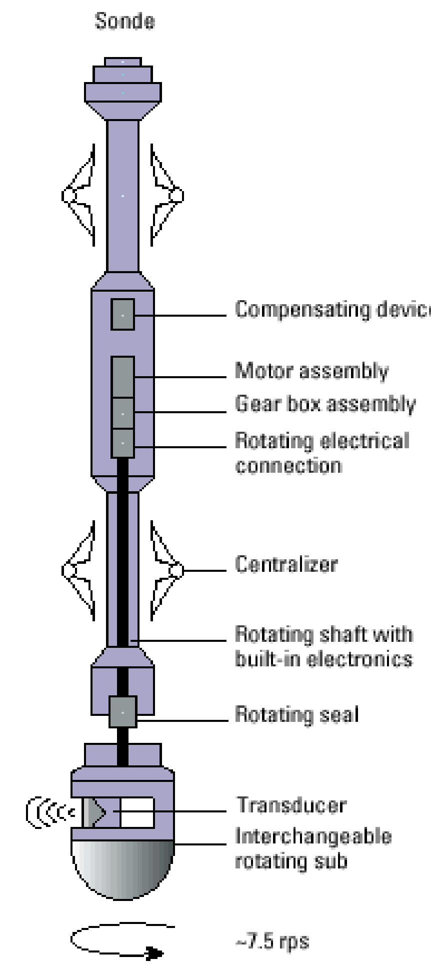
The transducer rotates at approximately 7.5 revs per second and is fired 72 times (every 5 deg) per revolution



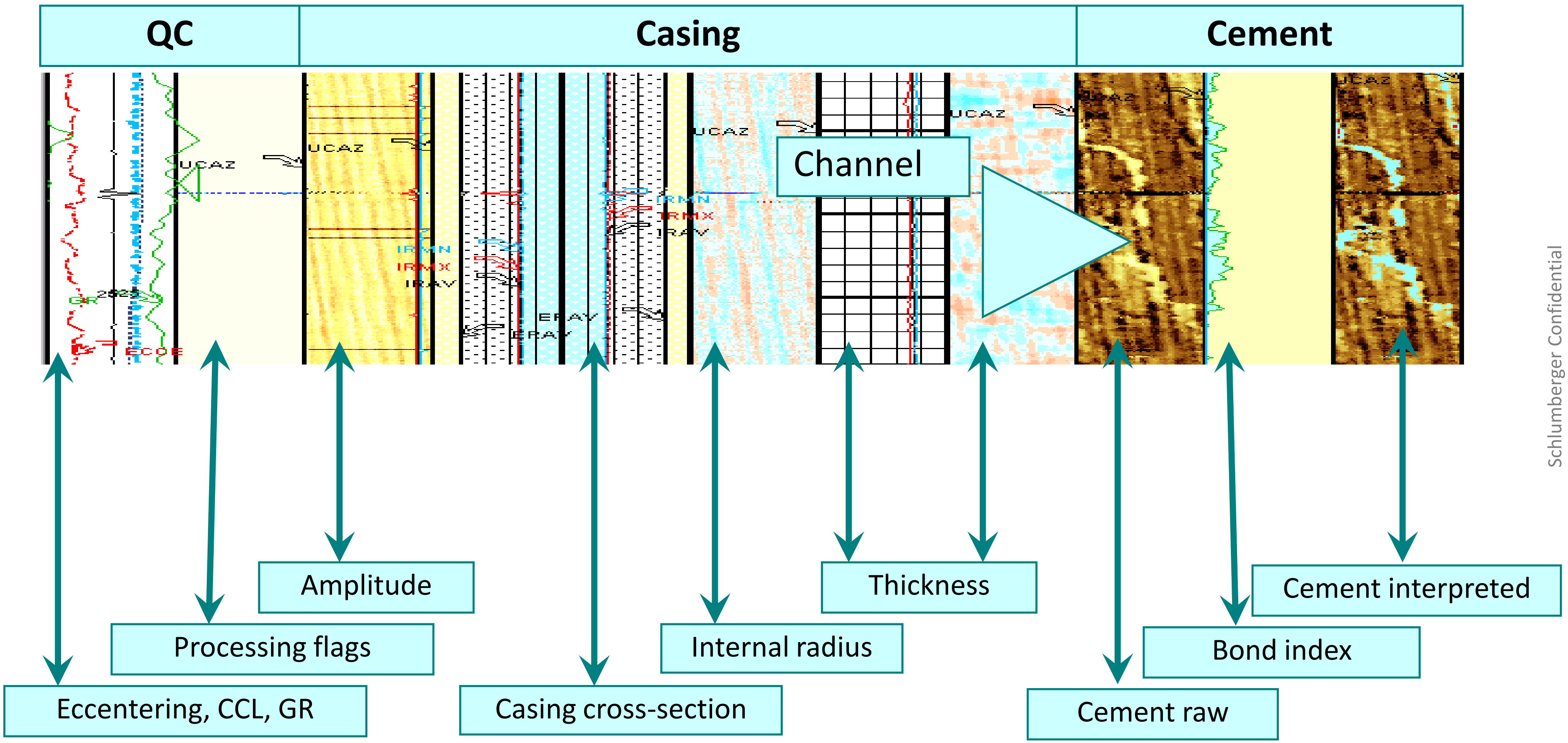


USIT Measurements





USIT Log Display



Cement Evaluation
Cement Bond Log and Ultrasonic Imager Tool

Measurement Specifications

	USIT
Output	Acoustic impedance, cement bonding to casing, internal radius, casing thickness
Logging speed	1,800 ft/h [549 m/h]
Range of measurement	Acoustic impedance: 0 to 10 Mrayl [0 to 10 MPa.s/m]
Vertical resolution	Standard: 6 in [15.24 cm]
Accuracy	Less than 3.3 Mrayl: ±0.5 Mrayl
Depth of investigation	Casing-to-cement interface
Mud type or weight limitations†	Water-base mud: Up to 15.9 lbm/galUS Oil-base mud: Up to 11.2 lbm/galUS
Combinability	Bottom only tool, combinable with most tools
Special applications	Identification and orientation of narrow channels

† Exact value depends on the type of mud system and casing size.

Mechanical Specifications

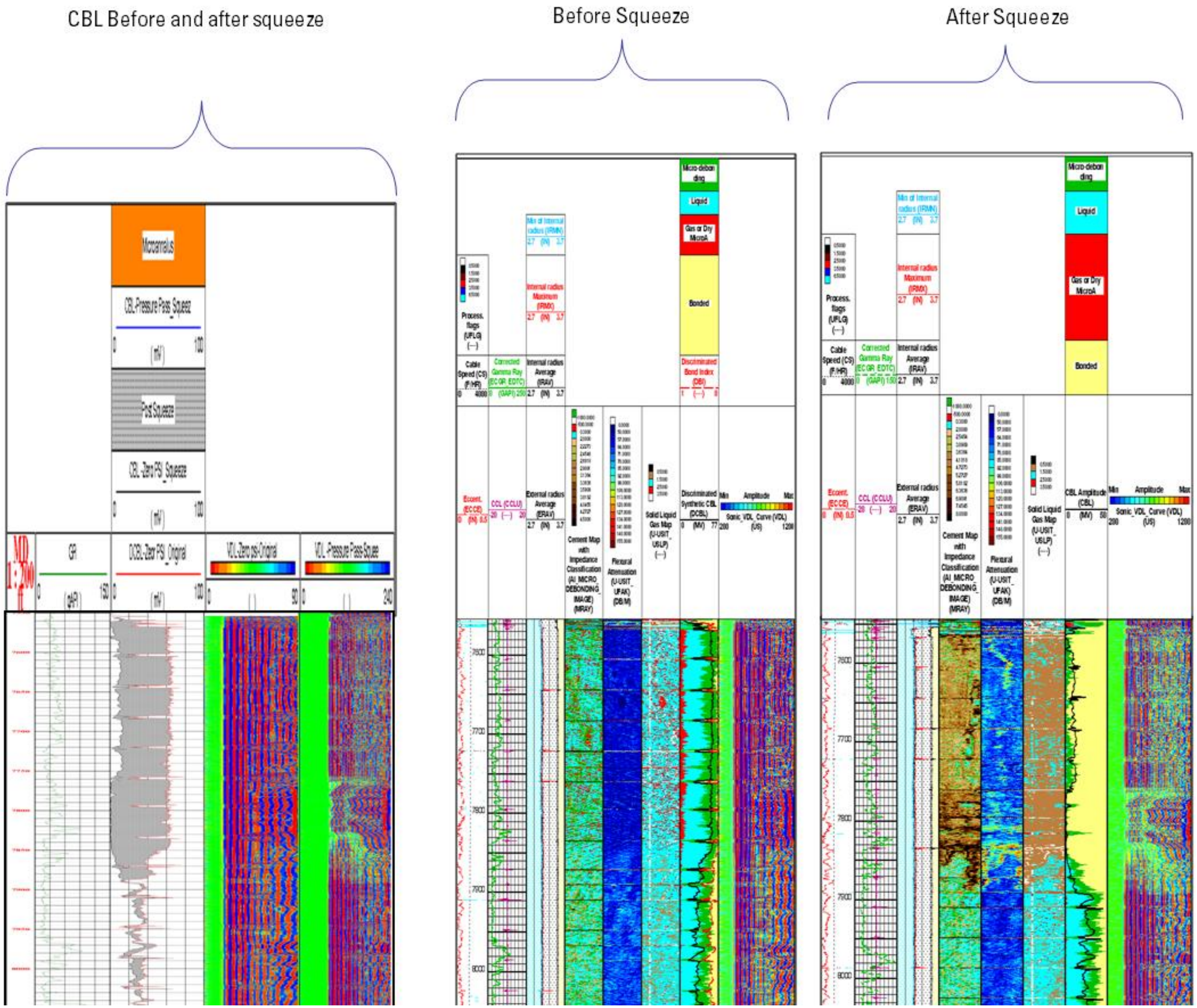
	USIT
Temperature rating	350 degF [177 degC]
Pressure rating	20,000 psi [138 MPa]
Casing size—min.	4½ in [11.43 cm]
Casing size—max.	13⅜ in [33.97 cm]
Outside diameter†	3⅜ in [8.57 cm]
Length†	19.75 ft [6.02 m]
Weight†	333 lbm [151 kg]
Tension	40,000 lbf [177,930 N]
Compression	4,000 lbf [17,790 N]

† Excluding the rotating sub

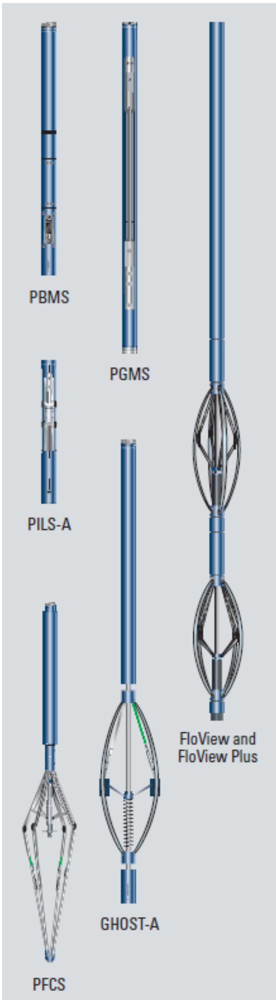
USIT Rotating Sub Mechanical Specifications

	USRS-AB	USRS-A	USRS-B	USRS-C	USRS-D
Outside diameter	3.41 in [8.66 cm]	3.58 in [9.09 cm]	4.625 in [11.75 cm]	6.625 in [16.83 cm]	8.625 in [21.91 cm]
Length	9.8 in [24.89 cm]	9.92 in [25.20 cm]	9.8 in [24.89 cm]	8.3 in [21.08 cm]	8.3 in [21.08 cm]
Weight	7.7 lbm [3.5 kg]	7.7 lbm [3.5 kg]	10.6 lbm [4.8 Kg]	15.0 lbm [6.8 kg]	18.3 lbm [8.3 kg]

Cement Example with Isolation Scanner



Production logging Measurements



Measurement Specifications	
	PS Platform System
Output	Flow rate, fluid density, pressure, temperature, water holdup, gas holdup, caliper, relative bearing, tool acceleration With SCMT: CBL, VDL, surface-readout radial cement map
Logging speed	Stationary to variable based on the application
Range of measurement	See individual sensor listing
Accuracy	See individual sensor listing
Depth of investigation	Borehole measurements
Mud type or weight limitations	Relatively clean fluids
Combinability	Combinable with SCMT tool and PS Platform Multifinger Imaging Tool (PMIT)
Special applications	Conveyance on drillpipe, tubing, coiled tubing, or slickline

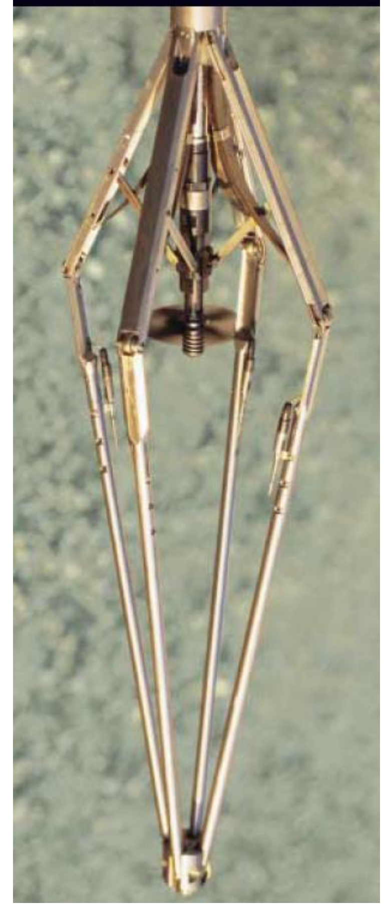
Mechanical Specifications	
	PS Platform System
Temperature rating	302 degF [150 degC] PILS: 350 degF [177 degC] High-temperature† and memory (only PBMS, PFCS, and PGMS sensors): 374 degF [190 degC] High-temperature† and surface readout (only PBMS, PFCS, and PGMS sensors): 392 degF [200 degC]
Pressure rating	Sapphire gauge: 10,000 psi [69 MPa] CQG and high-pressure Sapphire gauges: 15,000 psi [103 MPa]
Borehole size—min.‡	2⅜ in [6.03 cm]
Borehole size—max.	PFCS caliper: 11 in [27.94 cm] Other sensors: No limit
Outside diameter	Without rollers: 1.6875 in [4.29 cm] With rollers: 2.125 in [5.40 cm] High temperature: 2.06 in [5.23 cm]
Length§	PBMS: 8.27 ft [2.52 m] PFCS: 5.14 ft [1.57 m] PGMS: 4.8 ft [1.46 m] GHOST tool: 7.1 ft [2.16 m] FloView tool: 6.8 ft [2.07 m] PILS: 3.1 ft [0.94 m] UNIGAGE carrier: 4.2 ft [1.28 m]
Weight§	PBMS: 38.3 lbm [17.4 kg] PFCS: 19.7 lbm [9.0 kg] PGMS: 29.5 lbm [13.4 kg] GHOST tool: 57.7 lbm [26.2 kg] FloView tool: 16 lbm [7.3 kg] PILS: 12.5 lbm [5.7 kg] UNIGAGE carrier: 33 lbm [15 kg]

† High-temperature tools include the High-Temperature Basic Measurement Sonde (HBMS) and the High-Temperature Gradio Flowmeter tool (HGFT). These two components provide the same measurements as the PBMS, PGMS, and PFCS.

‡ Min. tubing size

§ The high-temperature tool (including all sensors) has a length of 23.94 ft [7.30 m] and a weight of 190.2 lbm [86.3 kg].

The Flow-Caliper Imaging tool integrates innovative sensors that provide the most important flow measurements only 16 in. [40 cm] from the bottom of the tool string.



Geothermal Production Logging Tool

Madden Geothermal PLT

Geothermal production logging tool

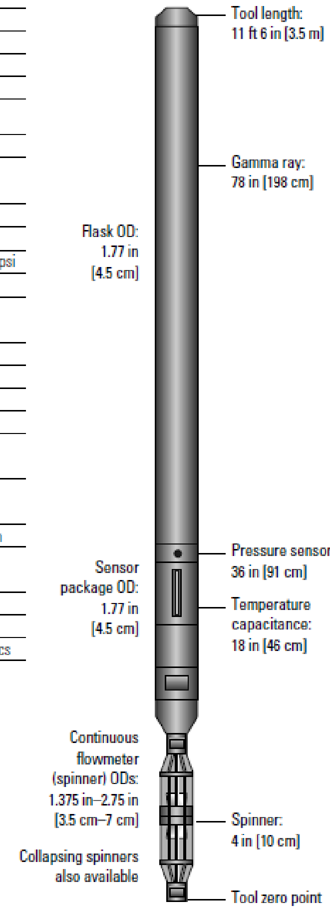
The Madden geothermal production logging tool (PLT) consists of a continuous flowmeter (spinner) and temperature, pressure, collar locator, and optional gamma ray sensors. Delta pressure calculations provide fluid identification. It is rated 650 degF but has been run at higher temperatures. The 1.77-in-OD tool was developed for surveillance of steam wells used in electricity generation.

This system records data to downhole memory in addition to sending data to the surface via the telemetry system. This allows for continued data acquisition and minimizes pulling out of the hole if surface communications are lost.

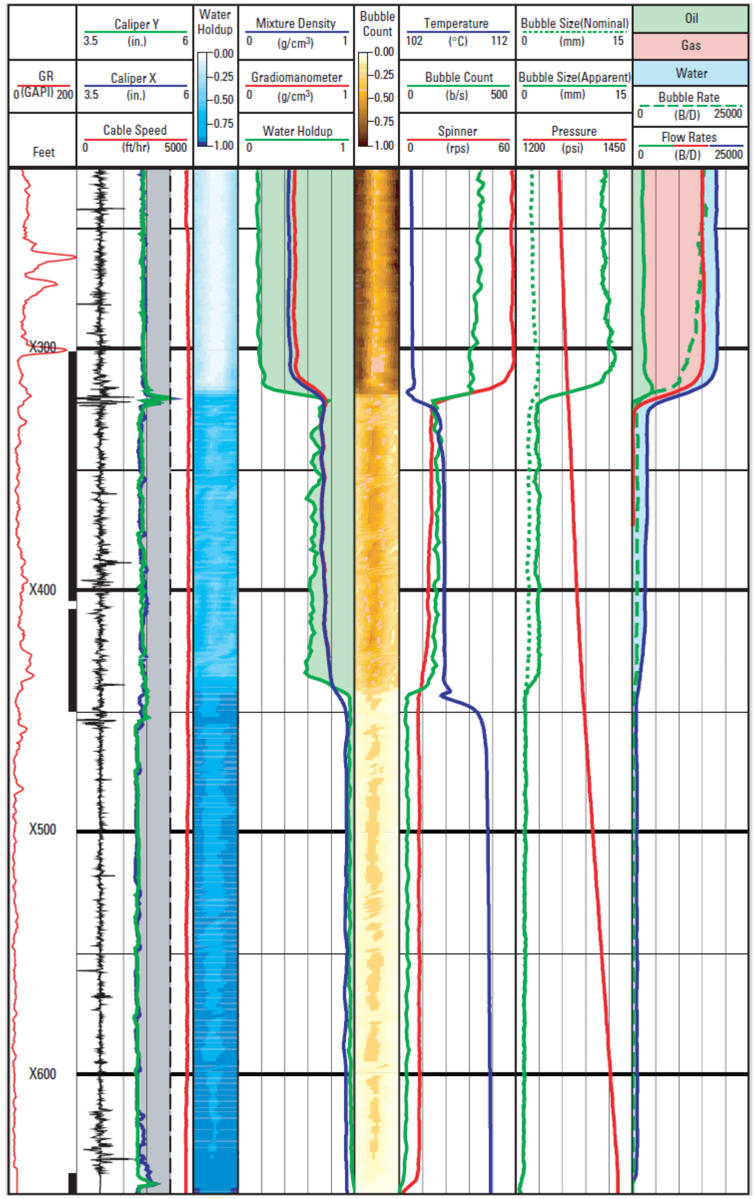
Onboard diagnostics allows correction and compensation of data while logging, providing quality control to cross reference acquired data to downhole events, rather than possible tool problems.

Mechanical Specifications	
Temperature rating	650 degF [343 degC]
Pressure rating	20,000 psi [138 MPa]
Maximum outside diameter	1.77 in [4.5 cm]

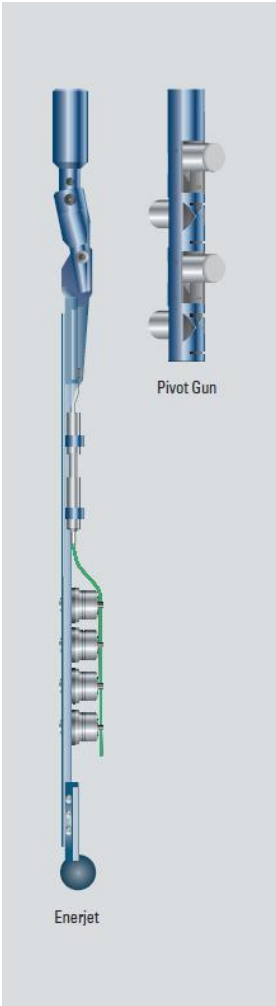
Measurement Specifications	
Pressure sensor	
Type	Quartz crystal
Resolution	0.01 psi
Accuracy	±0.03% full scale
Ranges	10,000, 16,000, and 20,000 psi
Make	Quartzdyne®
Temperature (borehole)	
Rating	650 degF [343 degC]
Type	Platinum RTD
Resolution	0.001 degC
Accuracy	±1 degC
Response	0–100 degC, 4 s
Gamma ray detector	
Type	Scintillation
Collar locator	
Type	Coil rare earth magnet
Capacitance	Dielectric fluid identification
Flowmeter (HD spinner)	
Type	Continuous and collapsing
Sensors	Reed switch/magnetic
Resolution	0.25 rps or 0.08 rps
Data status	Velocity/direction/diagnostics

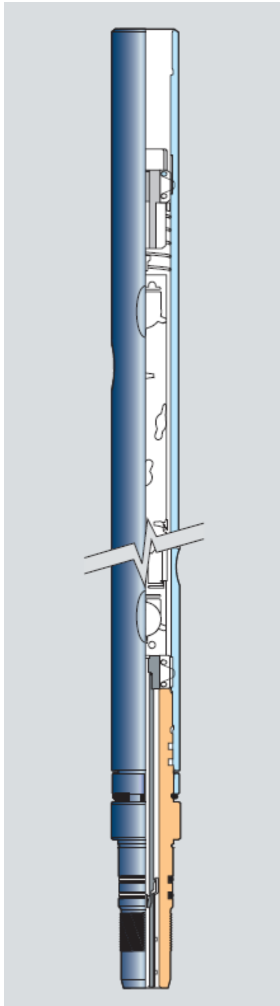


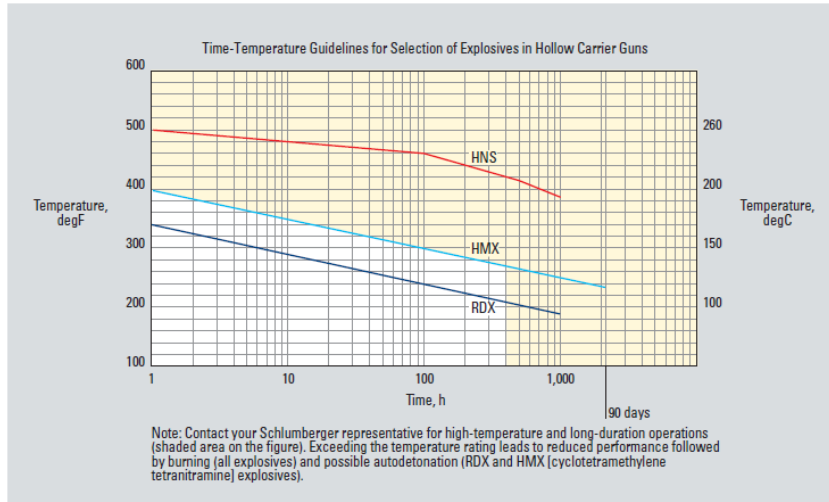
Production Log Example



Perforating Gun Systems







Case Studies and Examples

International School on Geothermal Exploration
1st Dec 2011

Jason Gendur
Petrophysics Domain Champion
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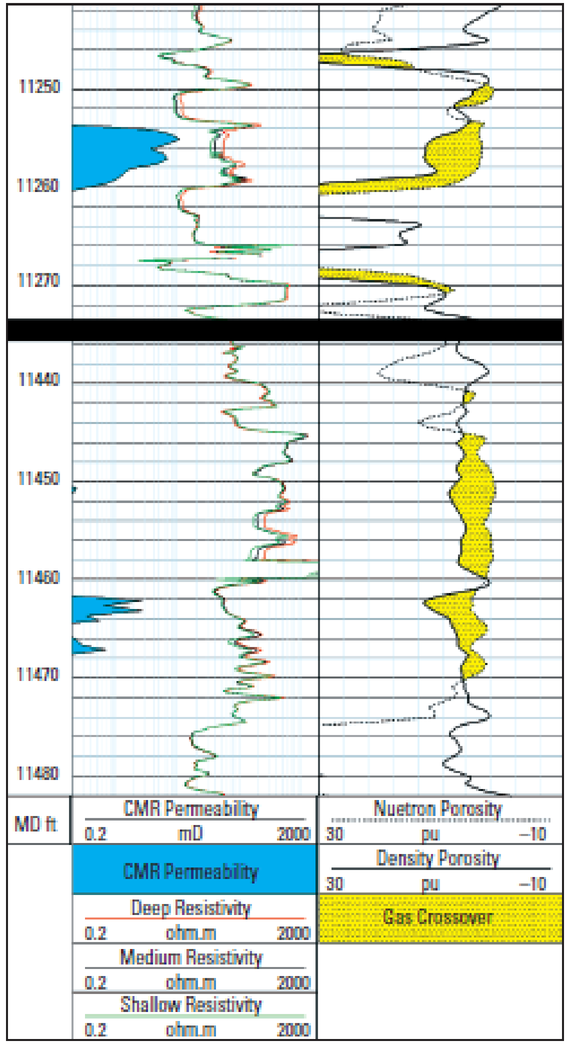
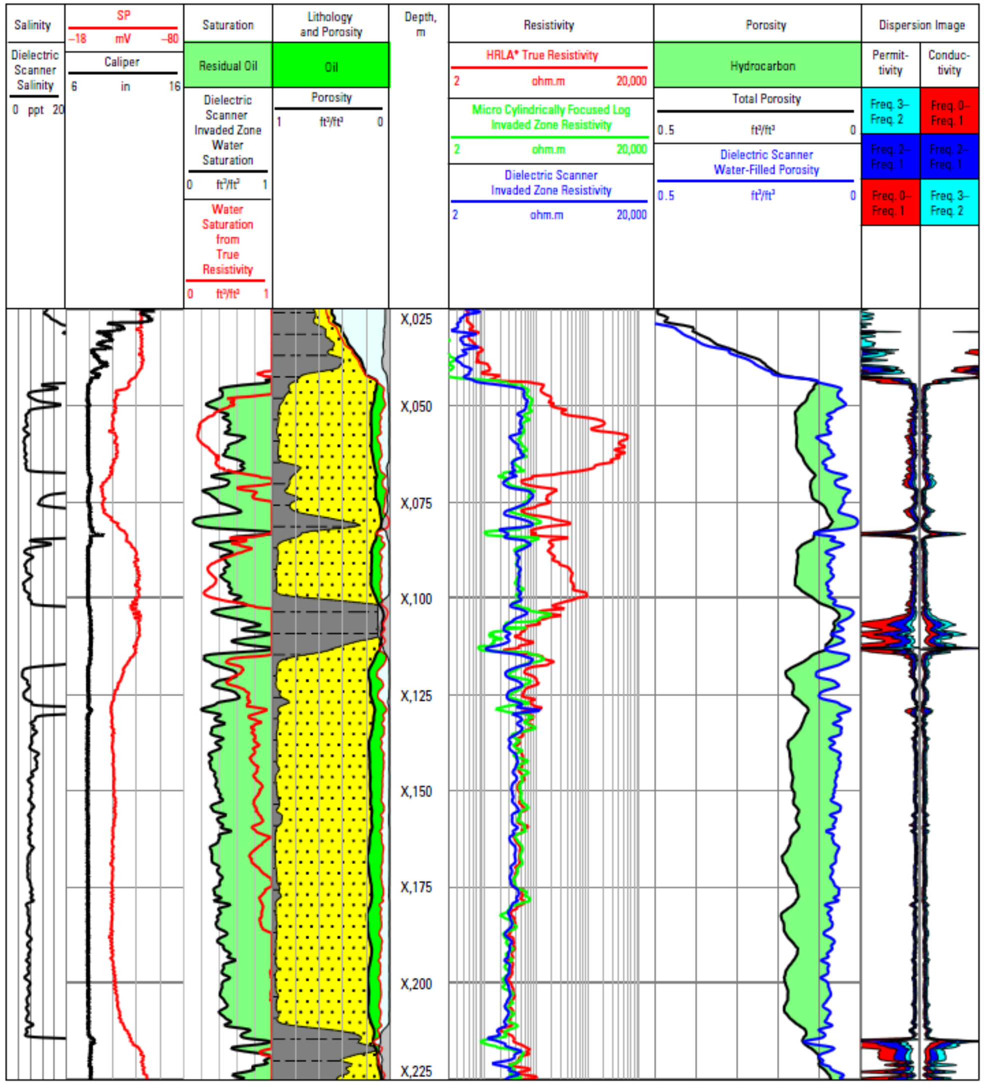
Schlumberger

Case study: Accurately Detect Permeable Layers



This CMR log accurately determined permeability values in the Morrow sands despite the difficult logging environment.

Case Study: Light Oil in Low Resistivity Reservoirs



Dielectric Scanner logging corrected the misestimated R_w value to improve interpretation and also find oil in the upper interval at X,125–X,215 ft.

Case Study: FMI to Identify Thin Beds

Challenge

Determine production potential of thinly bedded sands where conventional openhole logs failed to reveal pay intervals.

Solution

Use FMI* Fullbore Formation MicroImager logs to identify pay intervals.

Results

Interval completed with initial production of 16 MMcf/d of gas.

FMI log image analysis helped identify many thin sand lenses with low resistivity.

Production potential hidden without enhanced imaging

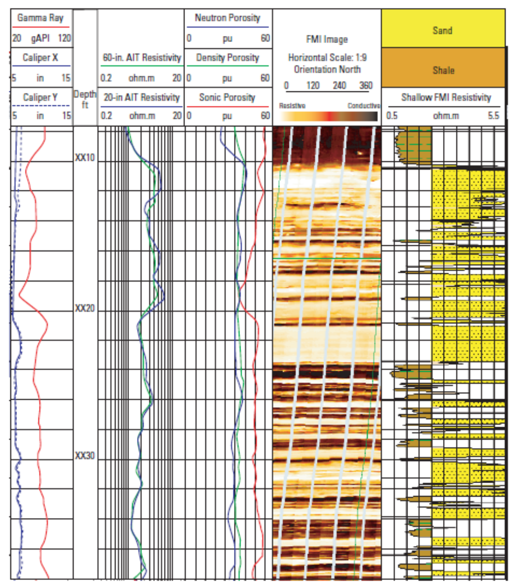
Using standard openhole logs, an operator believed that a formation of thinly bedded sands was not promising. Rather than miss additional potential production, better imaging was needed.

Improved images reveal potential production

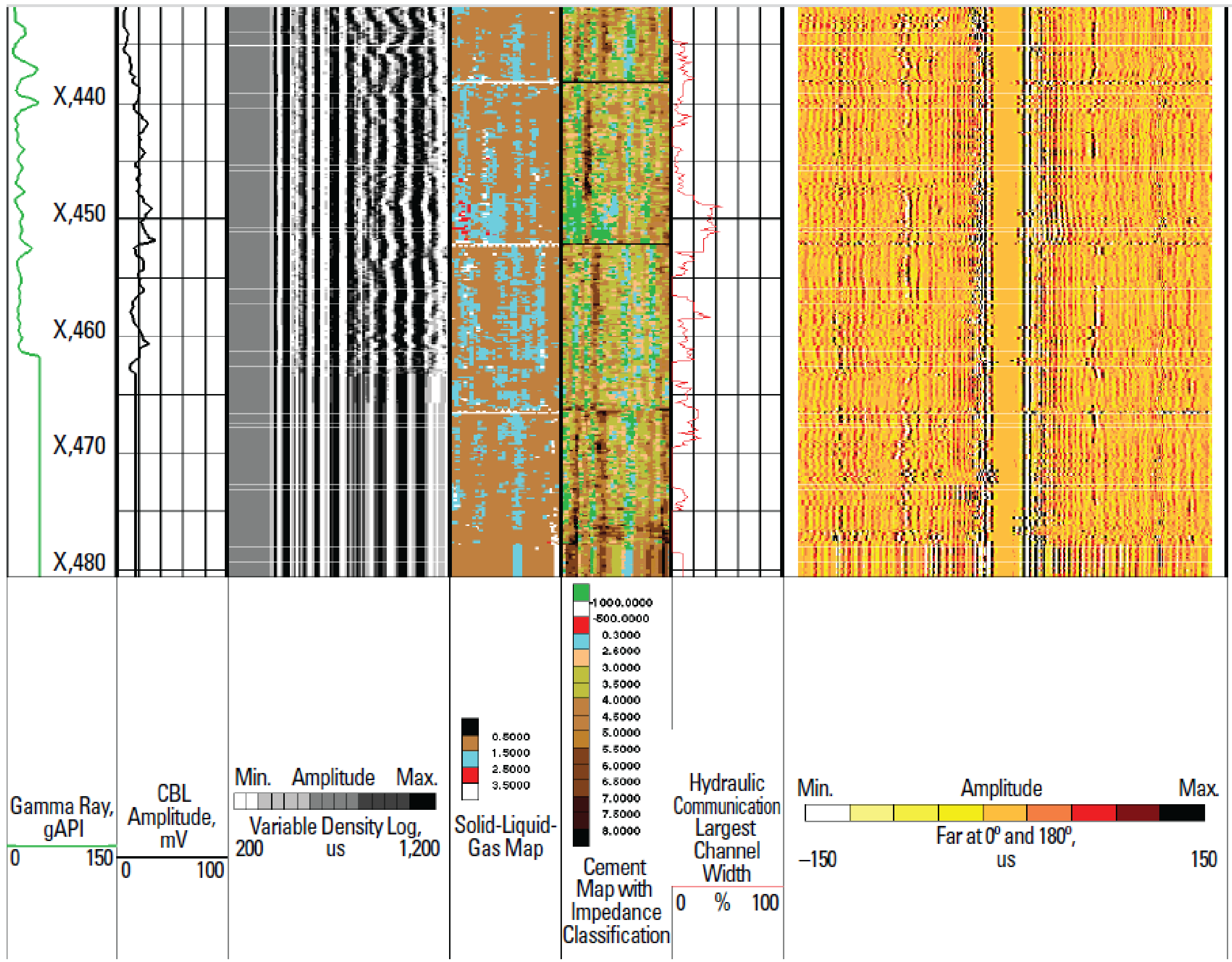
FMI image logs identify pay intervals in thinly bedded formations better than conventional logs can. The FMI tool was run and image analysis helped identify many thin sand lenses with low resistivity. Zones that had not initially appeared promising turned out to have production potential when the FMI images correlated with crossover of the neutron and density curves in the sand interval.

Interval completed

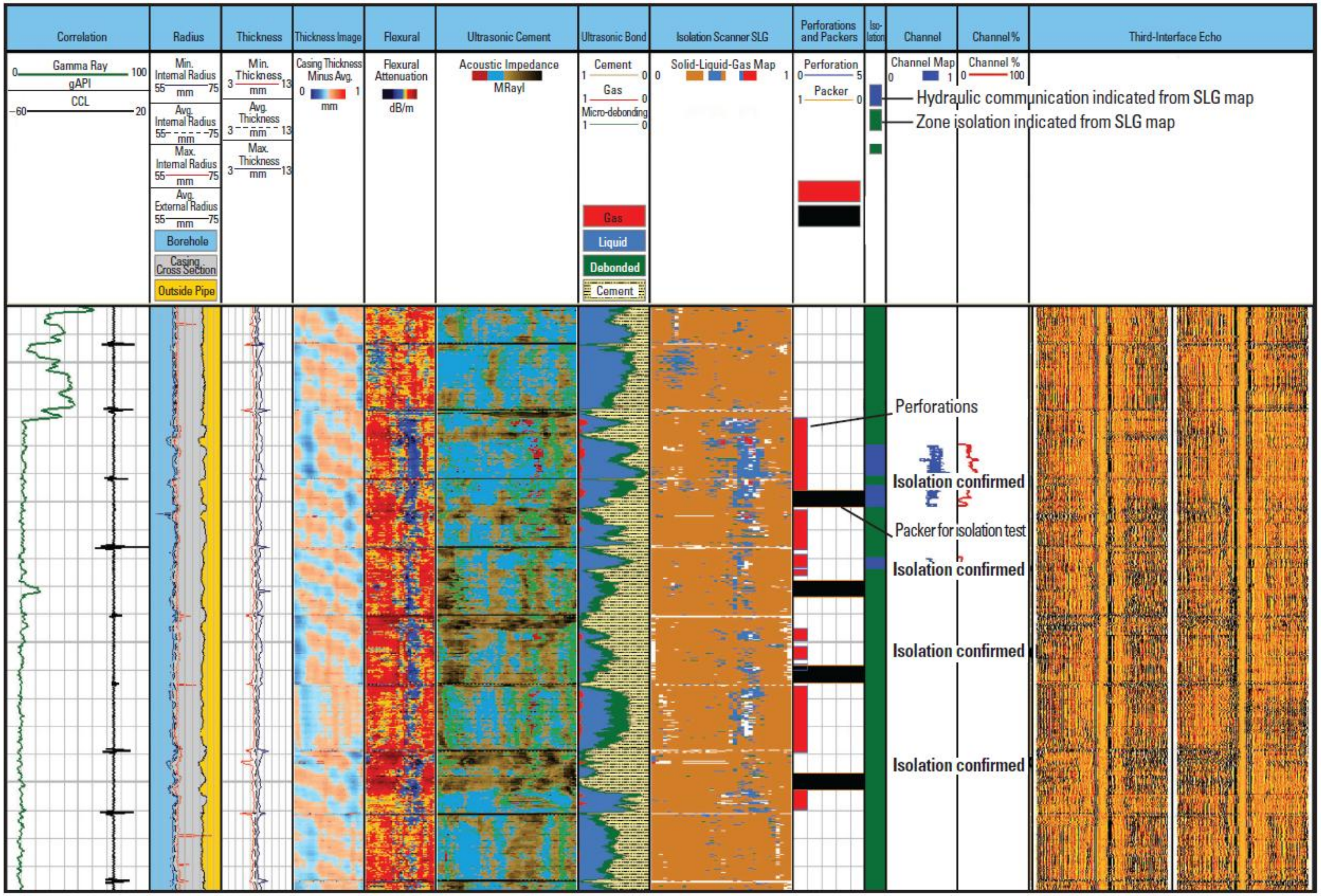
The operator completed the interval with initial production of 16 MMcf/d of gas.



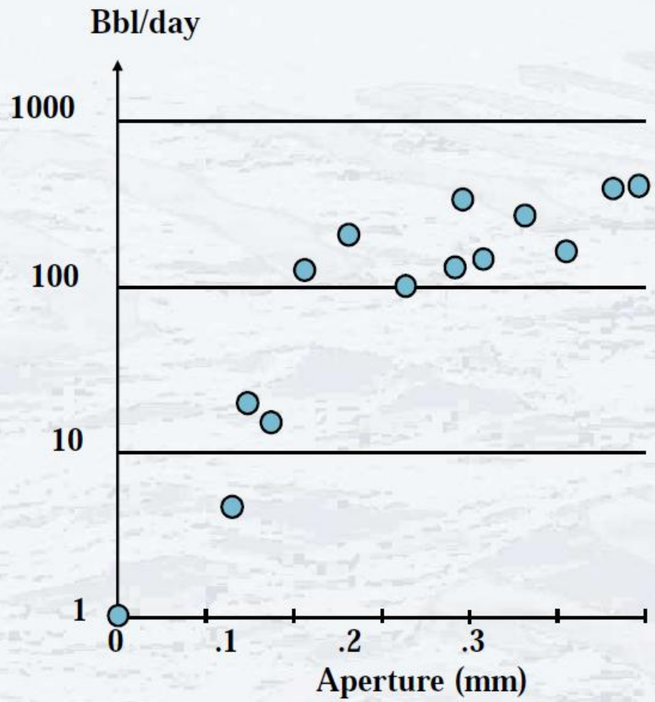
Case Study: Isolation scanner in Light Cement

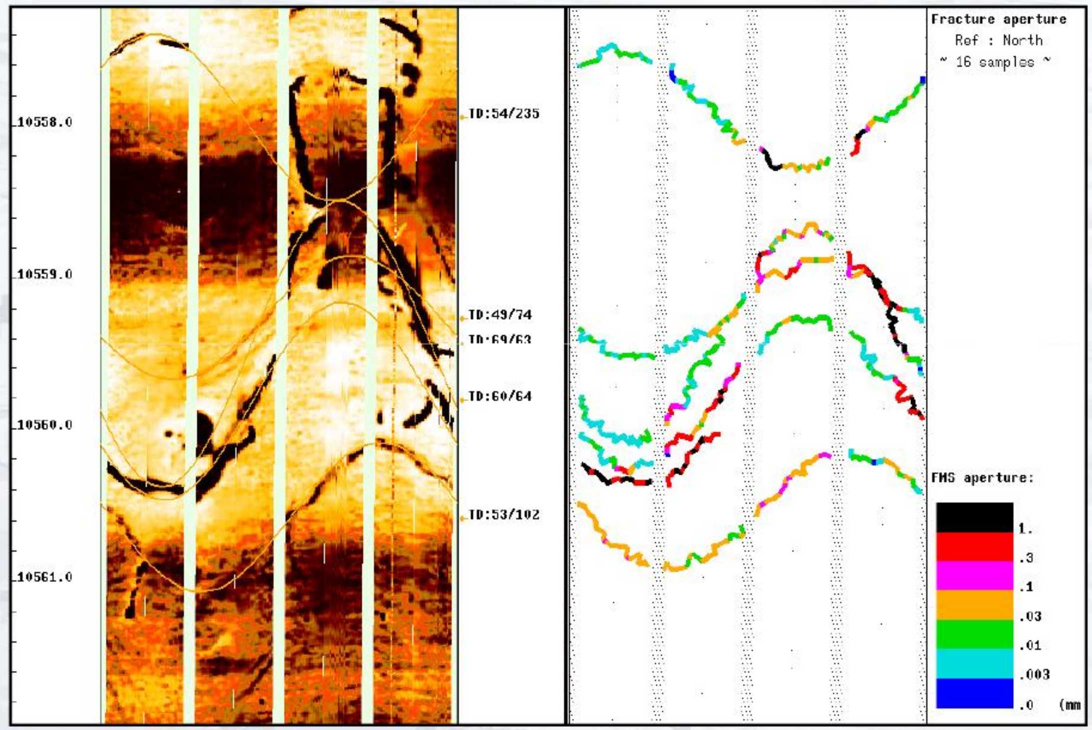


Case study: Isolation Scanner



Formation MicroImager Fracture Aperature

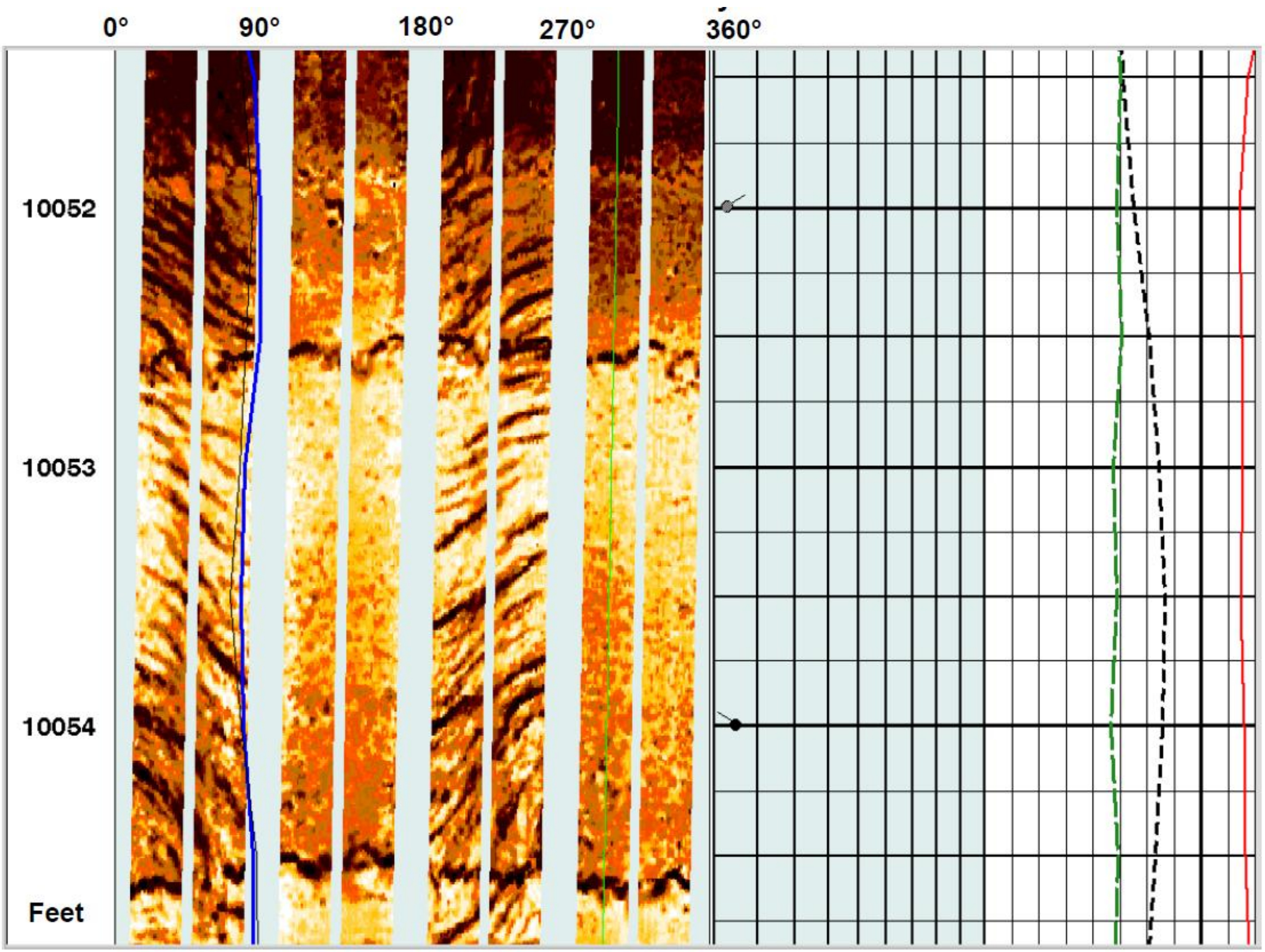




Fracture Aperture can be **estimated** from conductive fractures on FMI/FMS resistivity images

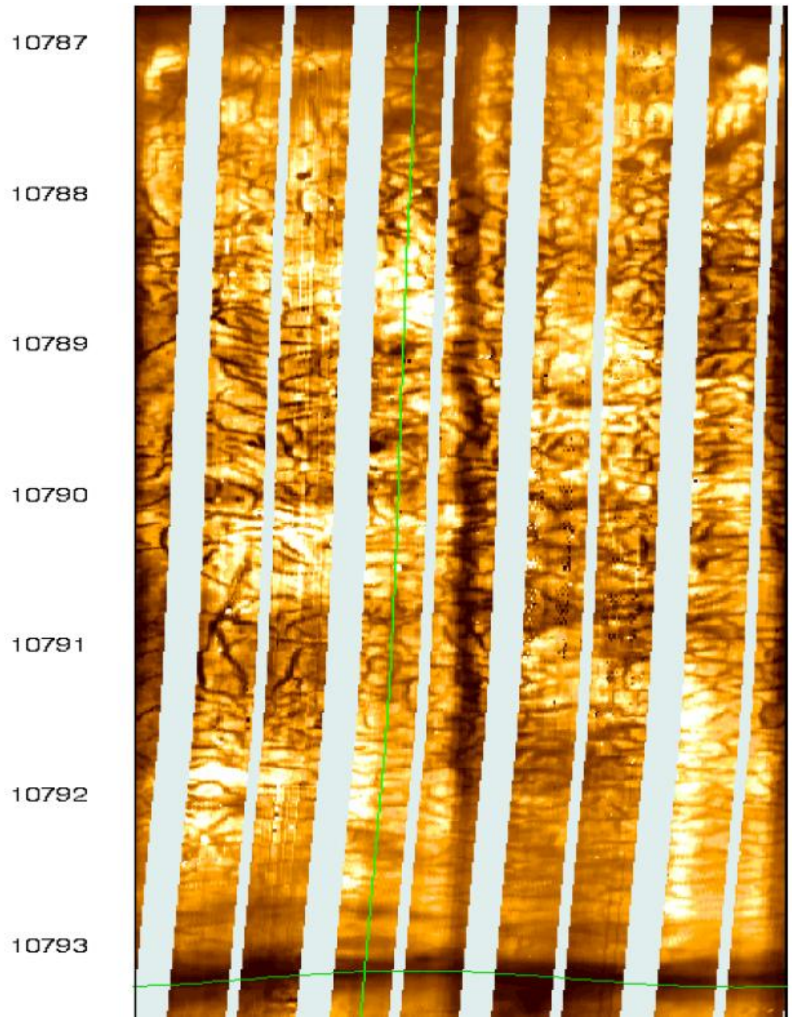
Courtesy: Emmanuel Bize

Mechanically Induced Fractures



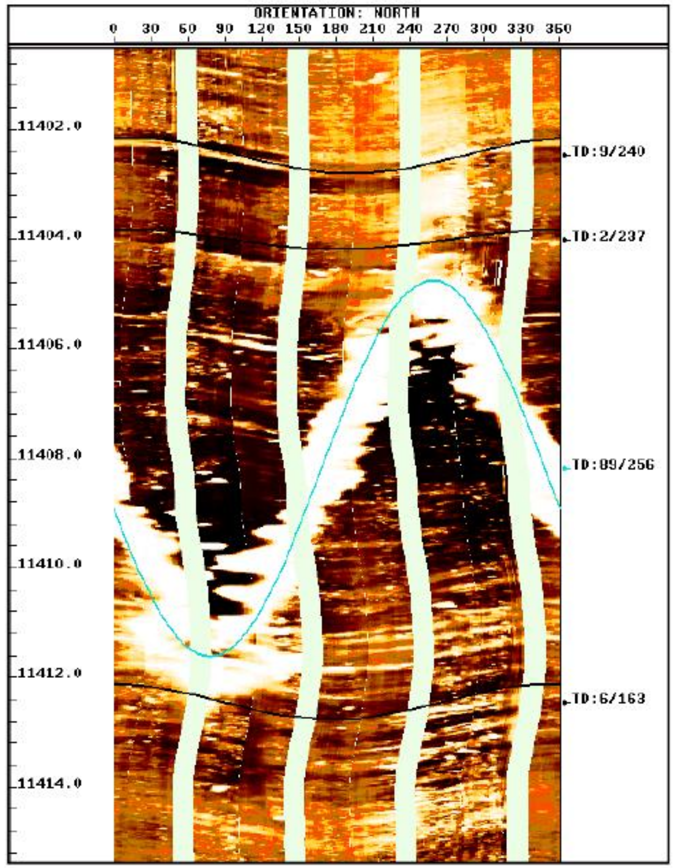
Courtesy: Emmanuel Bize

Polygonal and Mechanically Induced Fractures



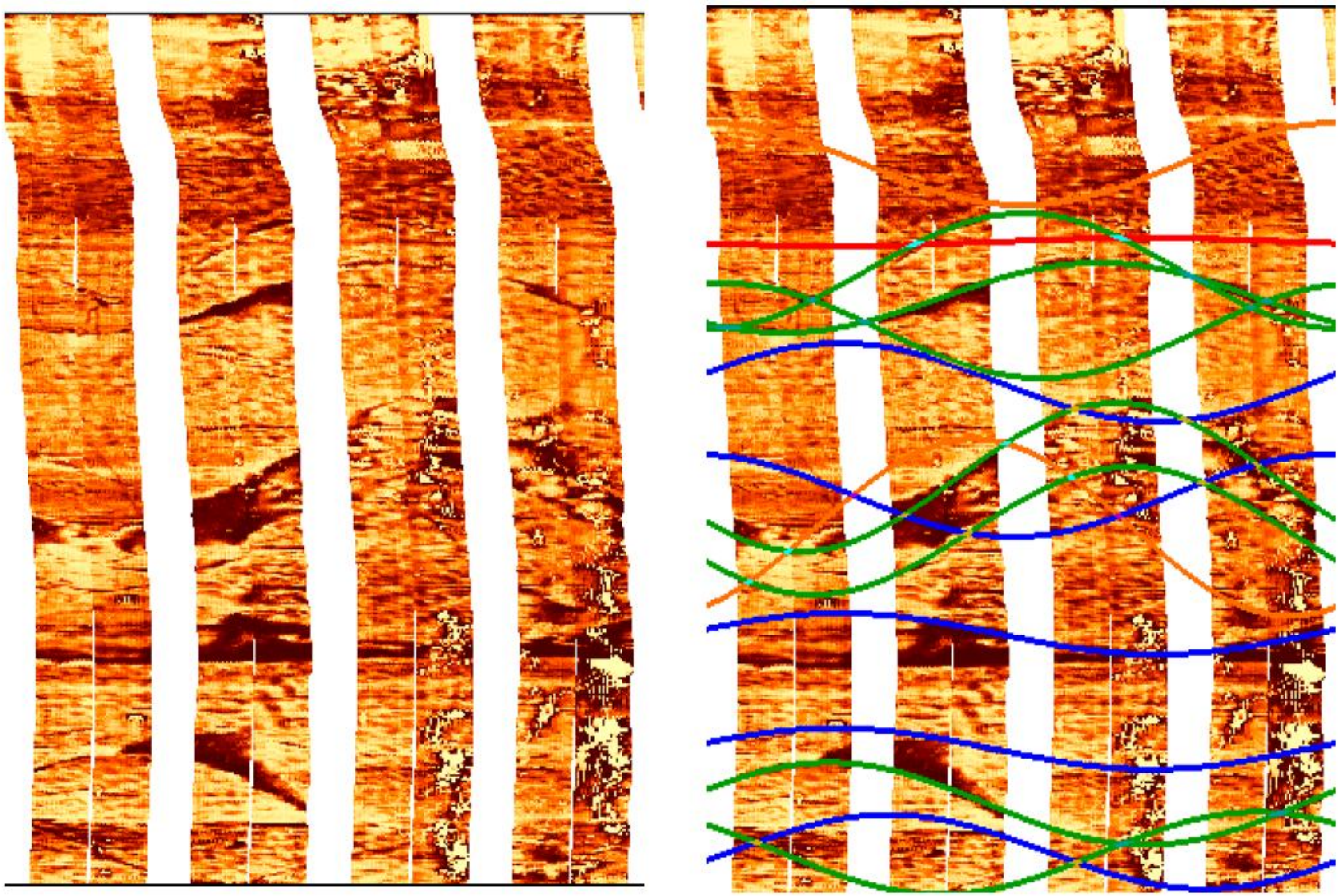
Courtesy: Emmanuel Bize

Healed Fracture



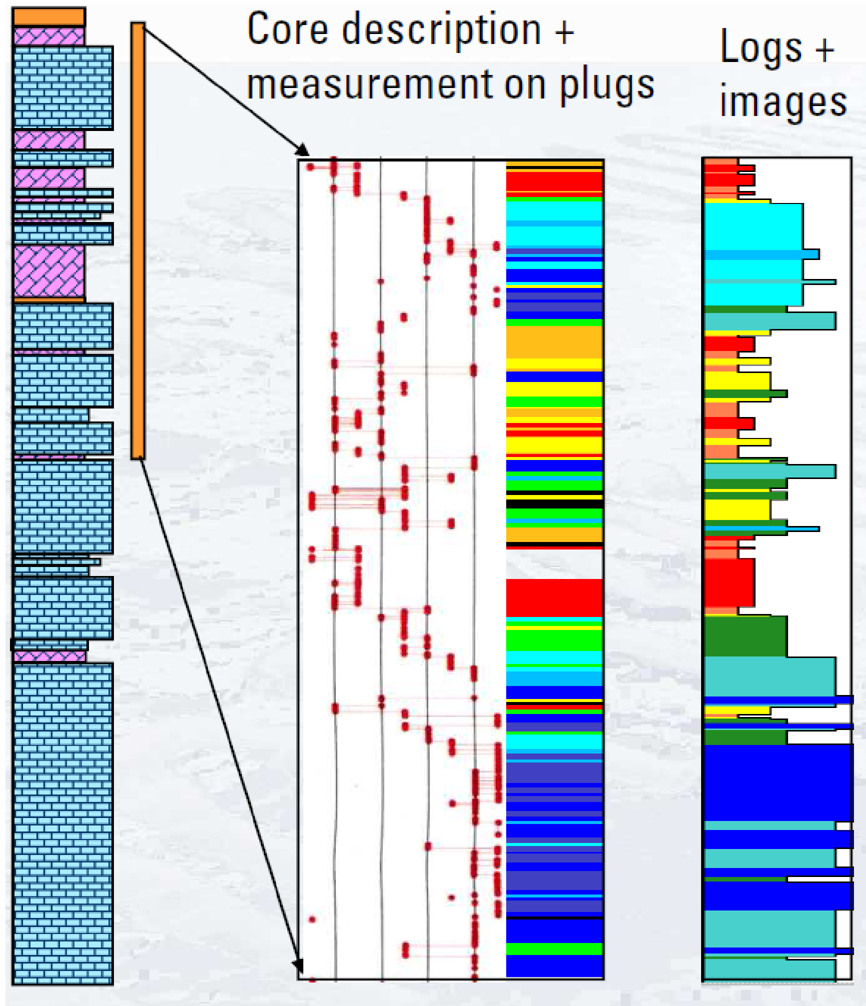
Courtesy: Emmanuel Bize

Complex Bedding



Courtesy: Emmanuel Bize

Facies Determination



Courtesy: Emmanuel Bize