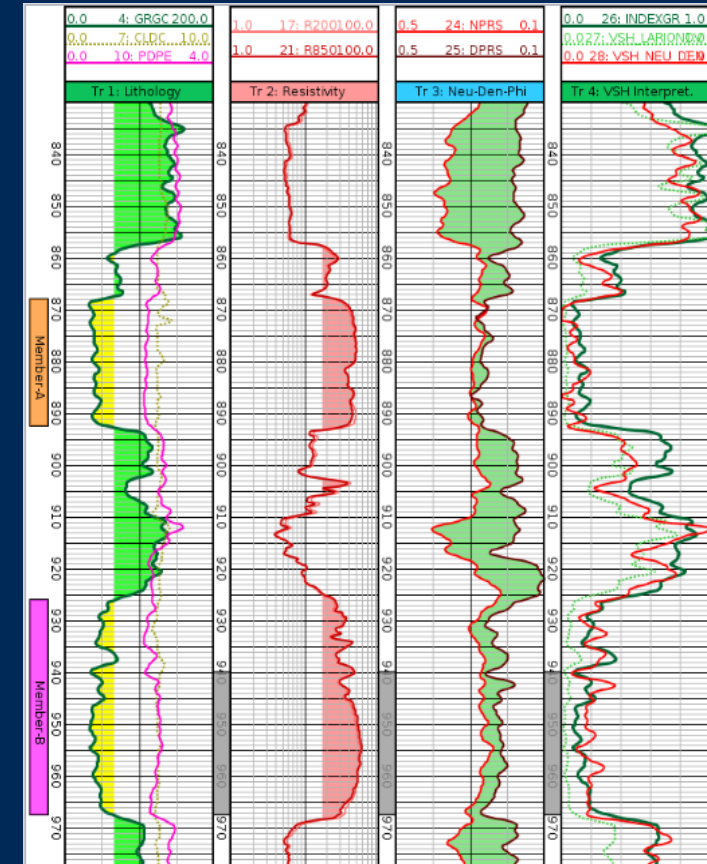


Sonic Log



Sonic Log Application

- ☐ Porosity determination
- ☐ Secondary porosity determination (combined with N-D logs)
- ☐ Lithology determination (combined with density log)
- ☐ Formation mechanical properties determination
- ☐ Determining R_{wa} (combined with resistivity log)
- ☐ Over-pressurized formation detection
- ☐ Cement bond log evaluation (cased hole log)
- ☐ Fracture detection
- ☐ Seismic studies

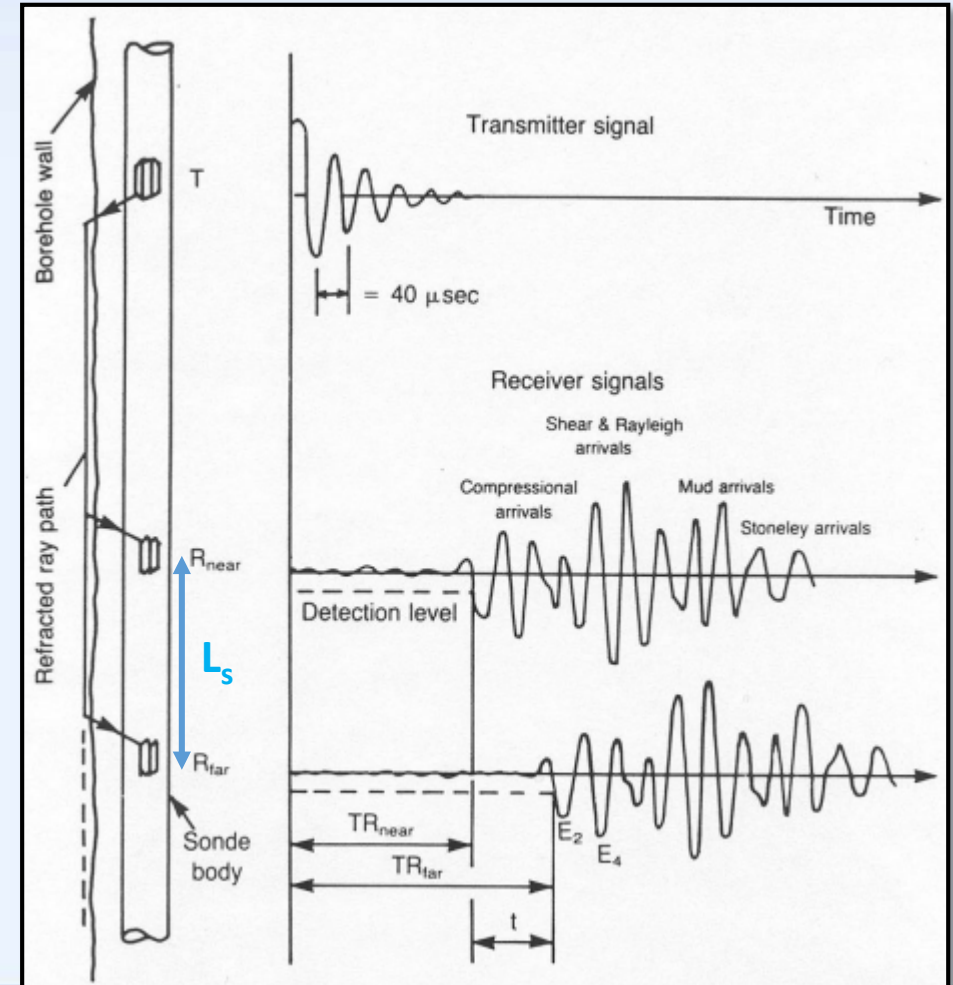
Sonic Tool Principle

- 1) A sound signal is emitted from the “Transmitter”.
- 2) Signal is recorded by “Receivers”.
- 3) Signal is analyzed based on :
 - Wave type(s)
 - Velocity/ transit time of the wave
 - Attenuation(loss of energy)

Transit(travel) time or slowness:

Difference in arrival of the compressional wave at receiver

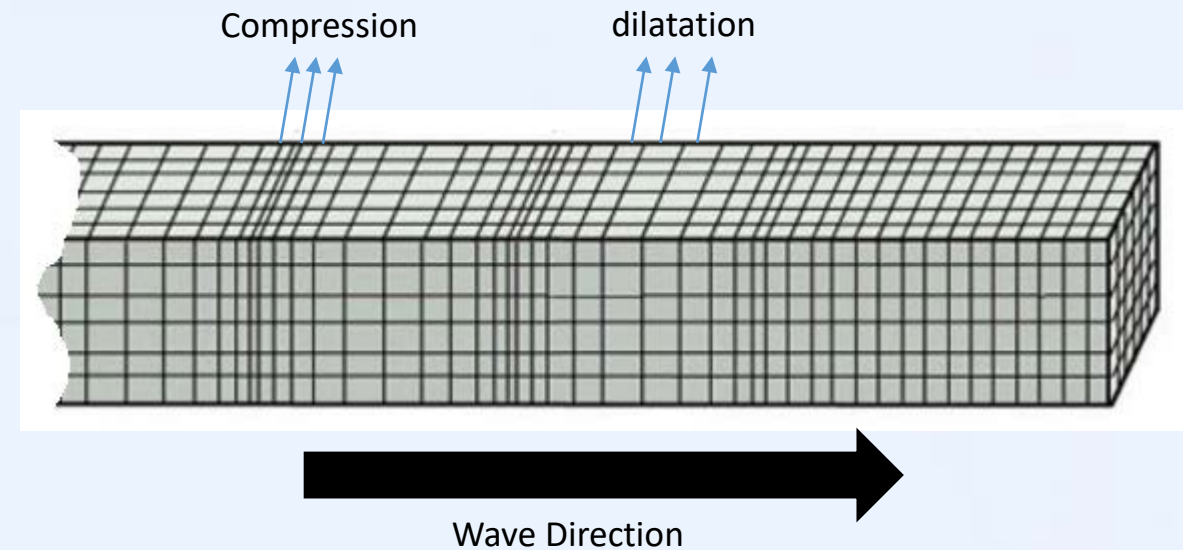
$$\Delta t = \frac{TR_{far} - TR_{near}}{L_s} \text{ } \mu\text{sec}/\text{ft} \quad V_c = \frac{10^6}{\Delta t} \text{ } \text{ft}/\text{sec}$$



From Schlumberger

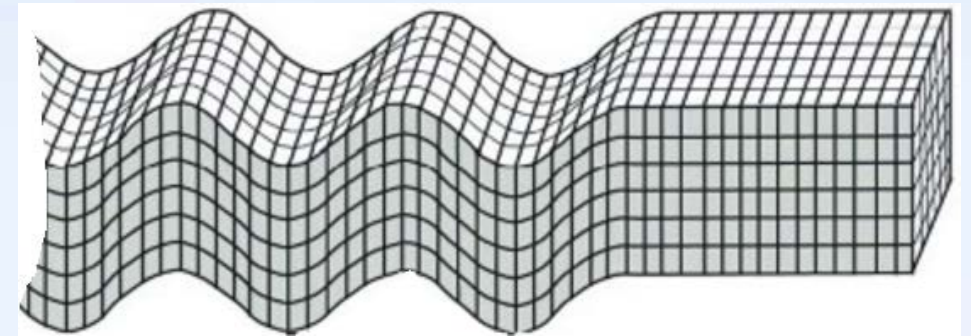
Compressional Wave

- Known as pressure wave (P-wave)
- Longitudinal waves
- Propagation direction || particle movement
- Passes through solid, liquid and gases.
- Speed solid > liquid > gas
- First arrival wave (fastest wave)
- Range in rock : 17390-25000 ft/sec (57.5-40 μ sec/ft)



Shear Wave

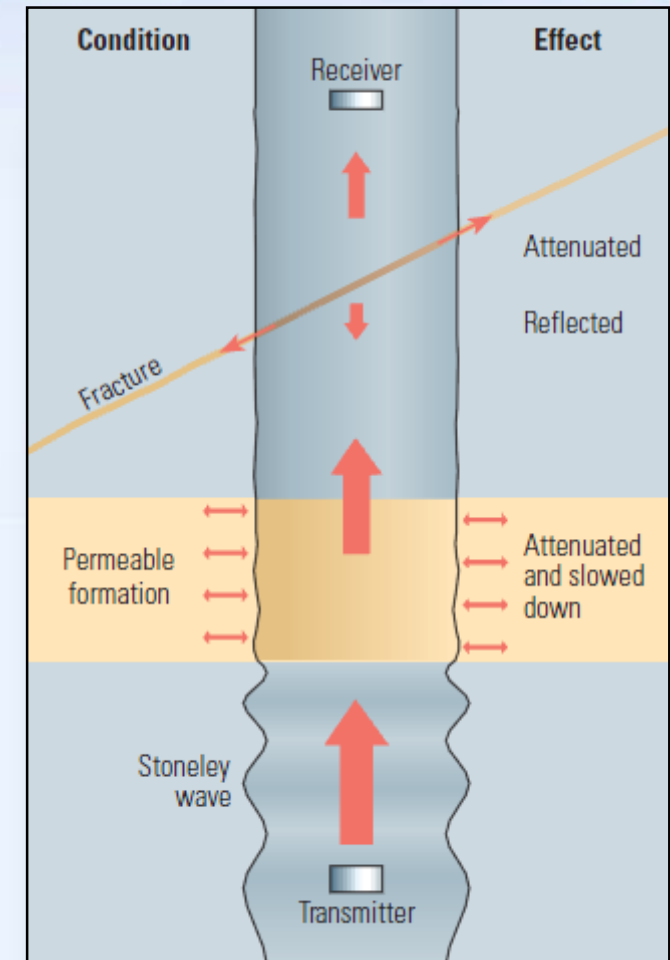
- Known as S-wave
- Transverse wave
- Propagation direction $\perp$ particle movement
- Propagates through solid.
- Does **NOT** propagate through gas and low viscous liquid.
- Some propagation in high viscous liquid with severe attenuation
- Second arrival wave (2nd fastest wave)
- $\Delta t_s / \Delta t_c (V_c / V_s)$ in formation: 1.6-2.3
- Sensitive to fractures



Wave Direction

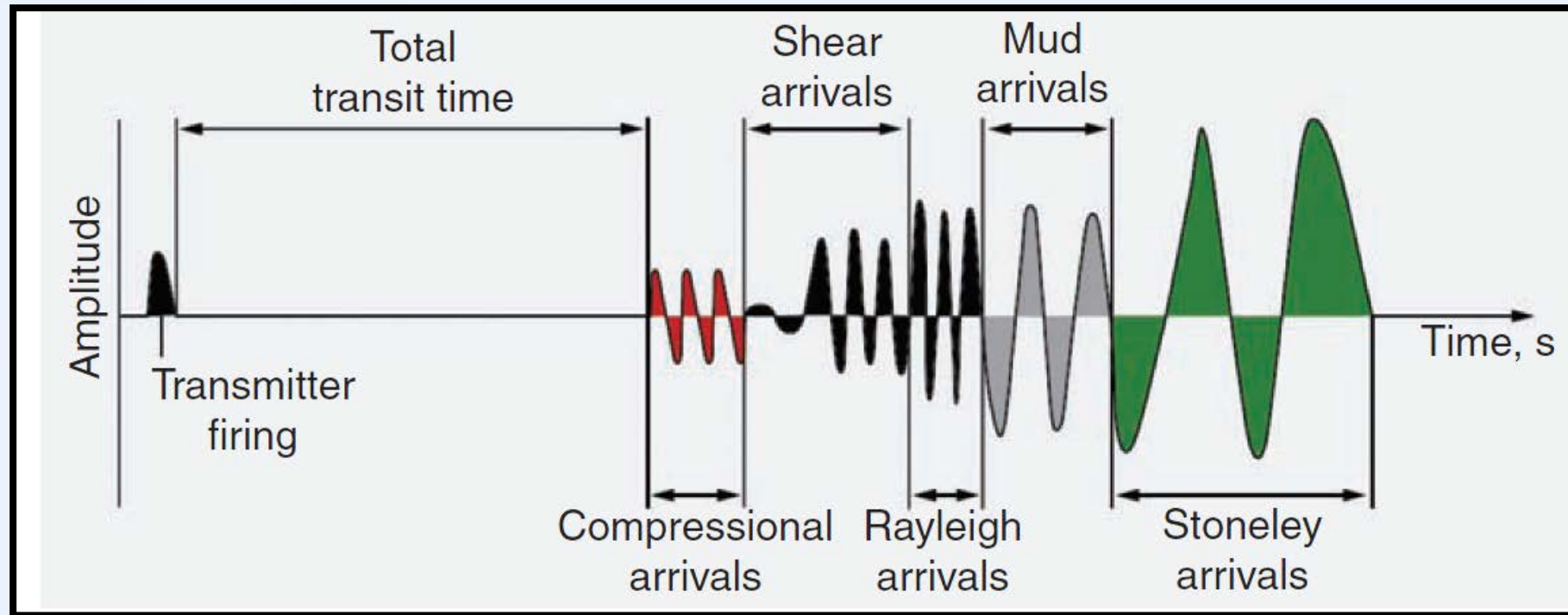
Stoneley Wave

- Travels at mud (in the wellbore) and formation interface
- Last arrival wave (slowest wave)
- Sensitive to permeability
- Sensitive to fractures



From Schlumberger

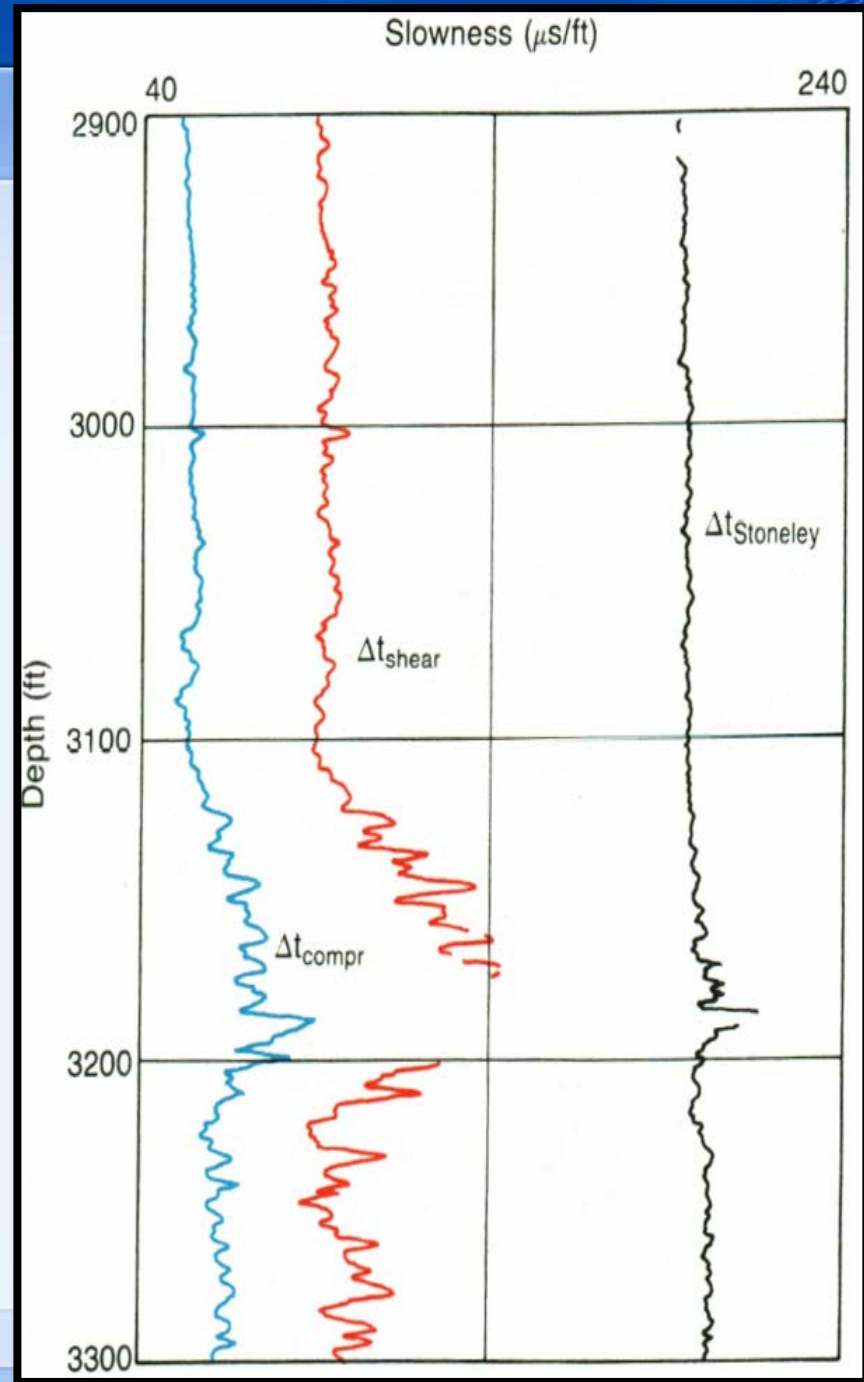
Sonic Log Waves



Bateman, 2012

Sonic Log

Sonic Waves



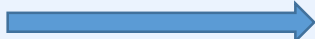
From Schlumberger

TABLE 16.3— Δt RATIO FOR ROCK TYPES
[AFTER MASON (1984)]

Formation Lithology	Ratio $\Delta t_s/\Delta t_c$
Anhydrite	2.45
Basalt	1.55
Chalk	2.45
Chert	1.6
Clay	3.2
Claystone	1.9
Diabase	1.7
Diorite	1.75
Dolomite	1.8
Epidosite	1.7
Gabbro	1.6
Gneiss	1.8
Granite	1.7
Gypsum	2.45
Hornstone	1.85
Limestone	1.9
Limestone (silty)	2.1
Limestone (argillaceous)	2.3
Marble	1.8
Mudstone	1.85
Pyrite	1.7
Quartz	1.55
Quartzite	1.5
Salt	2.15
Sandstone	1.6
Shale	1.7–1.75
Siltstone	1.8

Bateman, 2012

Sonic Tools

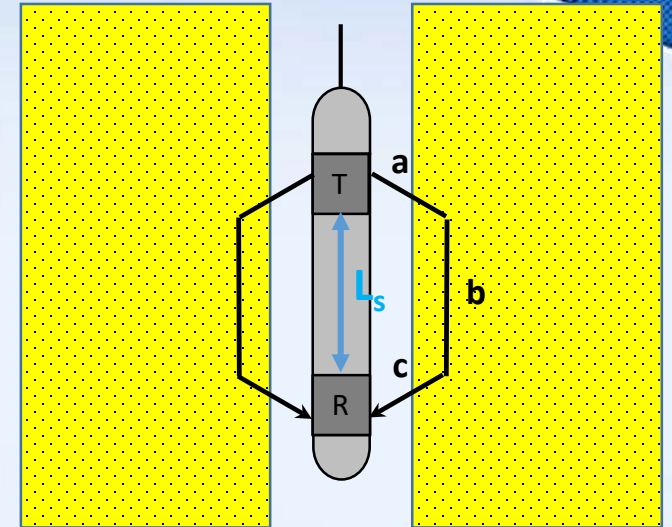
- ☐ Basic sonic (mono and dual receiver)  **Obsolete**
- ☐ Borehole Compensated (BHC)  **Most Common**
- ☐ Long Spacing Sonic (LSS)
- ☐ Array Sonic Tool
- ☐ Dipole Sonic Tool

Basic Sonic Tool

Mono Receiver

The measured travel time includes the travel time in mud (a & c) rather than formation (b)

$$T \text{ to } R = t_a + t_b + t_c$$



Dual Receiver

If tool is tilted or borehole size is not uniform (wash out), causes error.

$$T \text{ to } R_1 = t_a + t_b + t_c$$

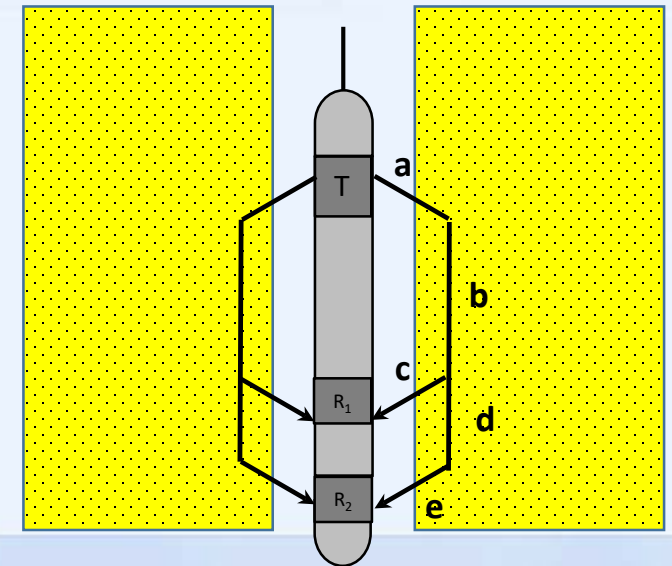
$$T \text{ to } R_2 = t_a + t_b + t_d + t_e$$

$$R_1 \text{ to } R_2 = t_d + t_e - t_c$$

If tool is axial

$$\downarrow t_e = t_c$$

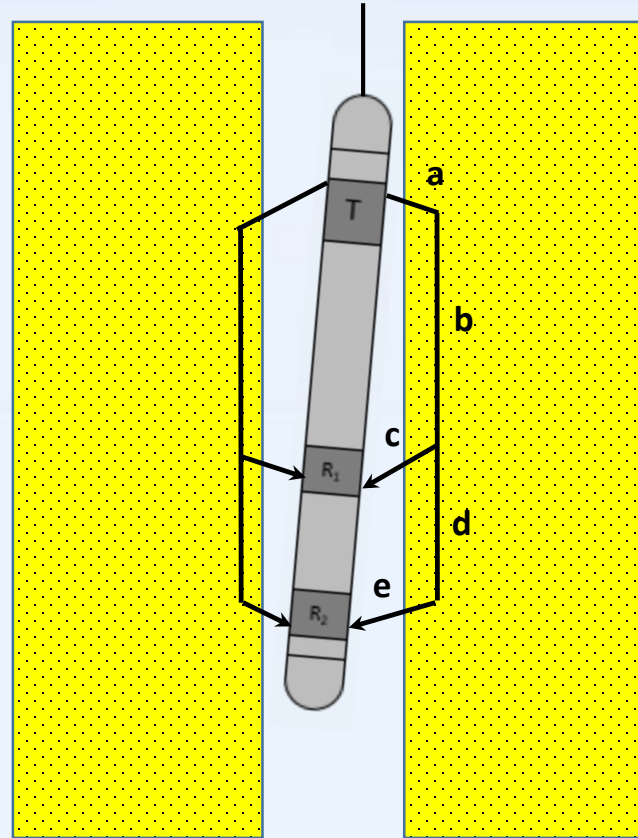
$$R_1 \text{ to } R_2 = t_d$$



Basic Sonic Tool

$$R_1 \text{ to } R_2 = t_d + t_e - t_c$$

$$t_e \neq t_c$$



BHC Tool

- One T & 2 R added to compensate wellbore effect
- 3 ft from T to near R
- 2 ft distance between pair Rs
- 1-2 inch depth of investigation
- 2 ft vertical resolution

Problem

Low DOI which causes error in reading of undisturbed zone transit time in shales.

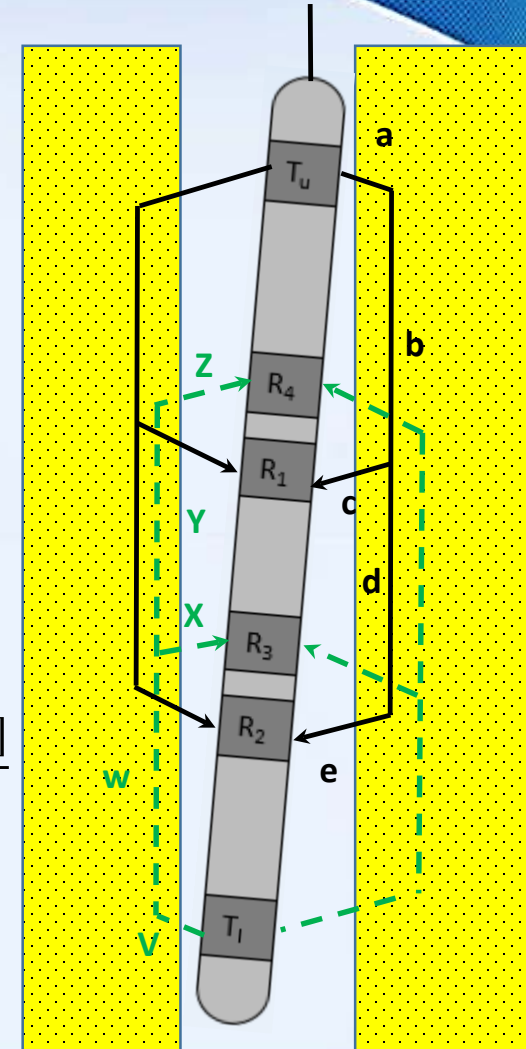
$$T_u \text{ to } R_1 = t_a + t_b + t_c$$

$$T_u \text{ to } R_2 = t_a + t_b + t_d + t_e$$

$$T_l \text{ to } R_3 = t_v + t_w + t_x$$

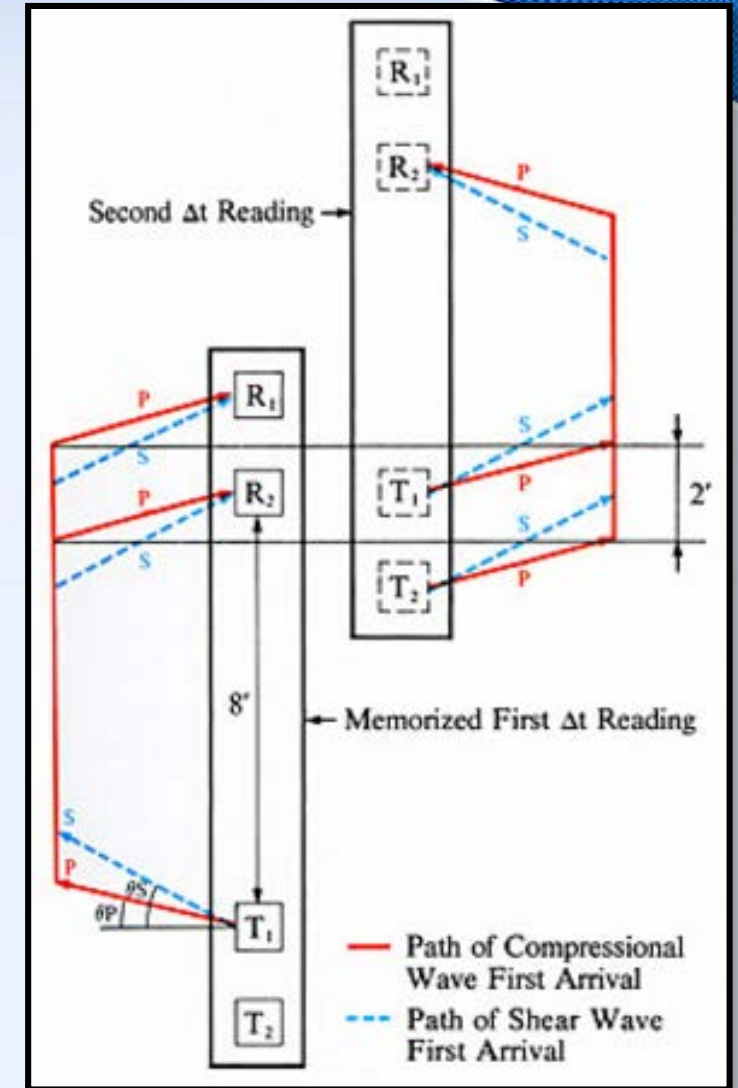
$$T_l \text{ to } R_4 = t_v + t_w + t_y + t_z$$

$$t = \frac{[(T_u \text{ to } R_2) + (T_u \text{ to } R_2)] - [(T_l \text{ to } R_4) + (T_l \text{ to } R_3)]}{2}$$



Long Spacing Sonic (LSS)

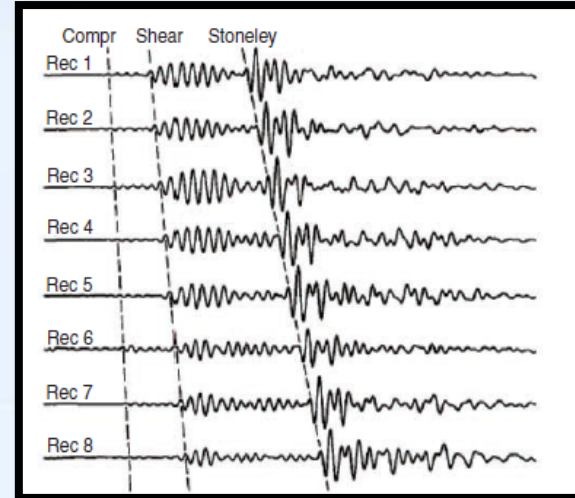
- 2 T and 2 R
- 8, 10, 12 ft from T to R
- 2 ft distance between pair Rs
- 6 inch depth of investigation (beyond damaged zone)
- 1-2 ft vertical resolution
- Compensation is achieved by memorizing



From Schlumberger

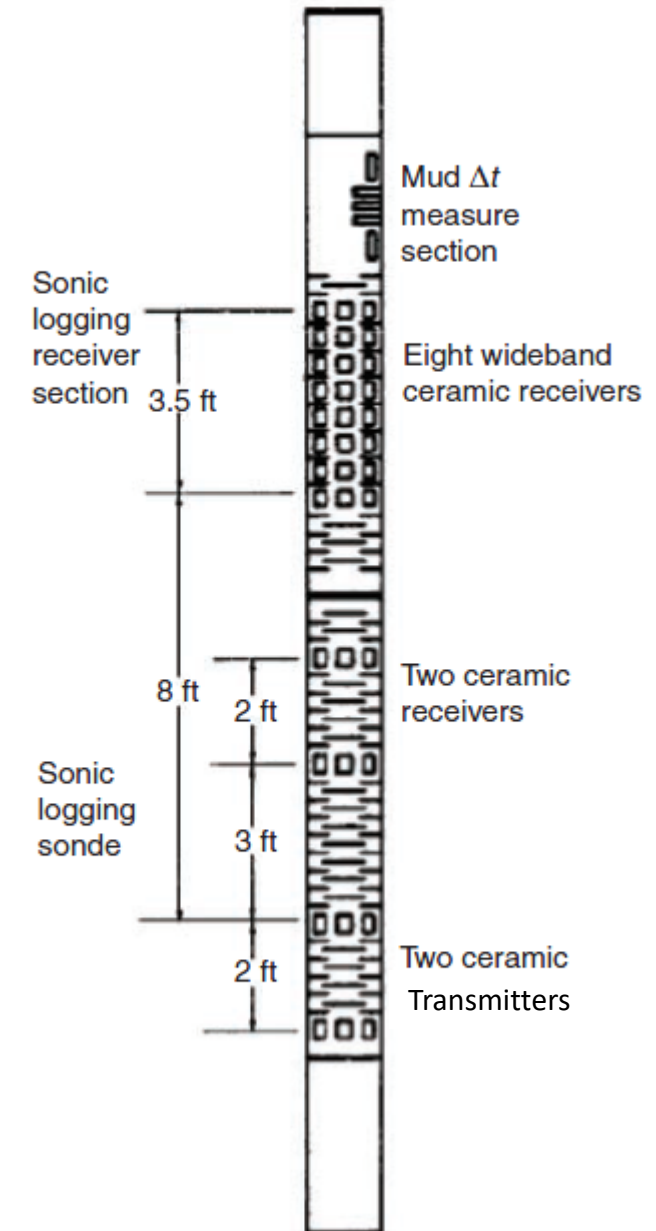
Array Sonic Tool

- 2 T and 10 R
- Combines LSS & BHC
- Records multiple different wave forms
- 2 ft distance between pair Rs
- 6 to 18" depth of investigation
- 6" vertical resolution
- Compensation is achieved by memorizing



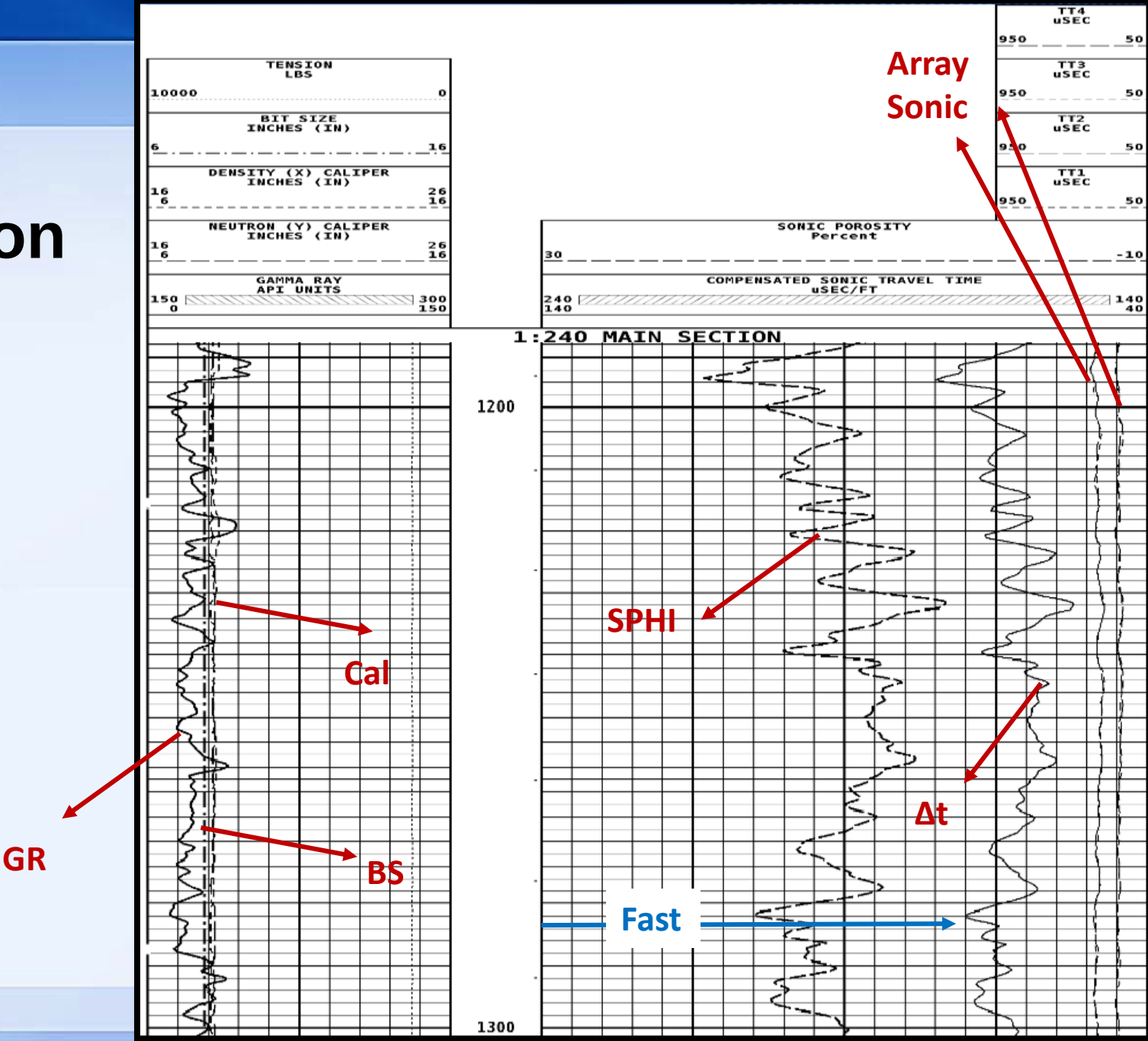
Dipole Sonic Tool

- Similar to Array Tool
- Incorporates P & S waves



Log Presentation

- Linear
- Increases right to left



Sonic Porosity

Wyllie Time-Average Equation

$$\phi_s = \frac{\Delta t - \Delta t_{ma}}{\Delta t_f - \Delta t_{ma}}$$

Consolidated formations

Fluid	ϕ	Δt_f
Matrix		
	Δt_{ma}	
	$1 - \phi$	

$$\Delta t = \phi \times \Delta t_f + (1 - \phi) \times \Delta t_{ma}$$

Δt from log

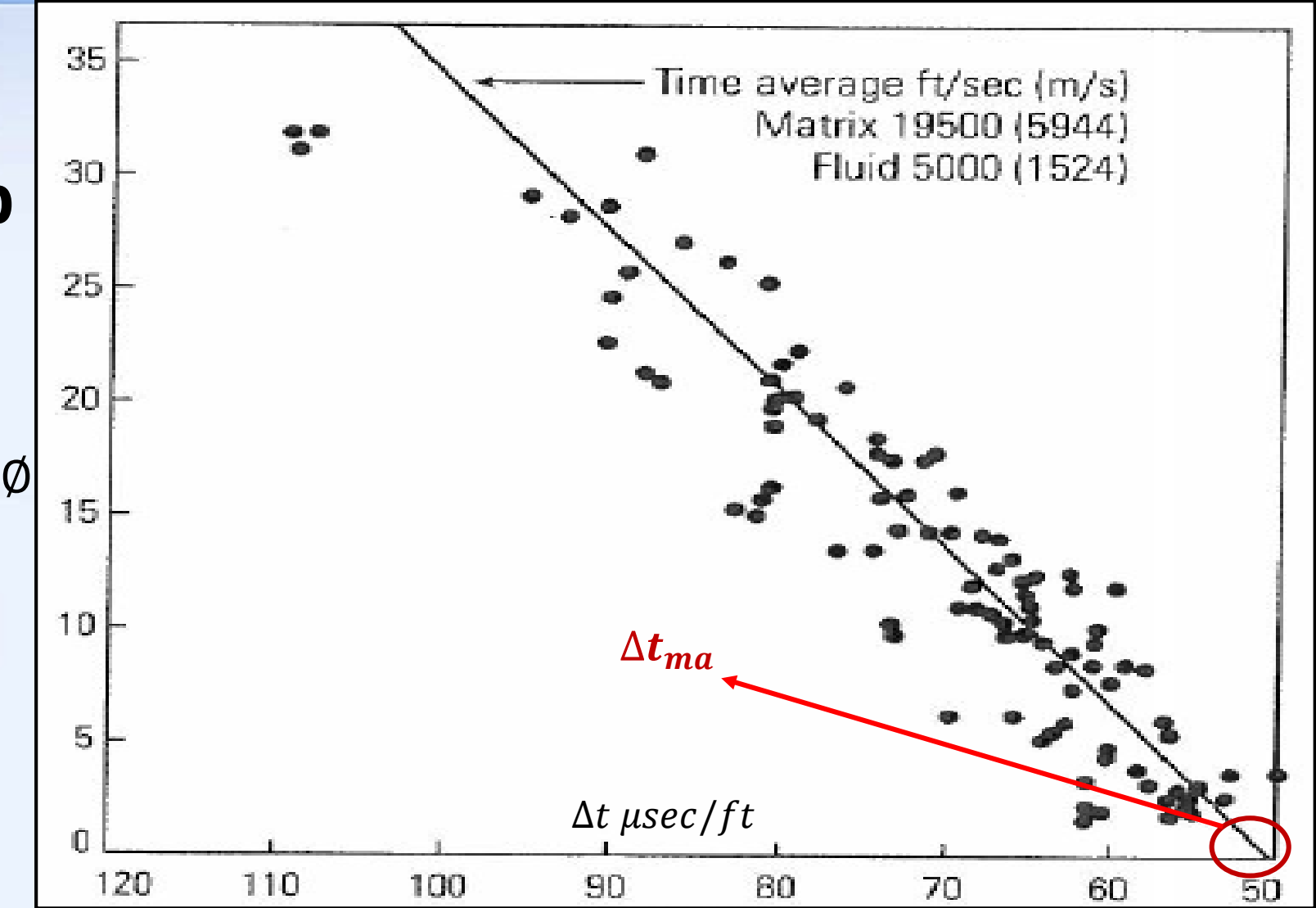
Raymer-Hunt-Gardener (RHG) Equation

$$\phi_s = 0.7 \frac{\Delta t - \Delta t_{ma}}{\Delta t}$$

Δt in Common Materials

	Material	Travel Time Δt ($\mu\text{s}/\text{ft}$)	Velocity (ft/sec)	Density g/cm^3
Δt_{ma}	Dolomite	43.5	23,000	2.87
	Limestone	47.5	21,000	2.71
	Sandstone	55.6	18,000	2.65
	Anhydrite	50.0	20,000	2.97
	Gypsum	52.5	19,000	2.35
	Salt	67.0	15,000	2.03
Δt_f	Water (fresh)	200	5,000	1.00
	Water (100,000 ppm NaCl)	189	5,300	1.06
	Water (200,000 ppm NaCl)	176	5,700	1.14
	Oil	232	4,300	
	Air	919	1,088	
	Casing	57	17,000	

Measuring Δt_{ma} in Lab



Wyllie, 1961

Sonic Log

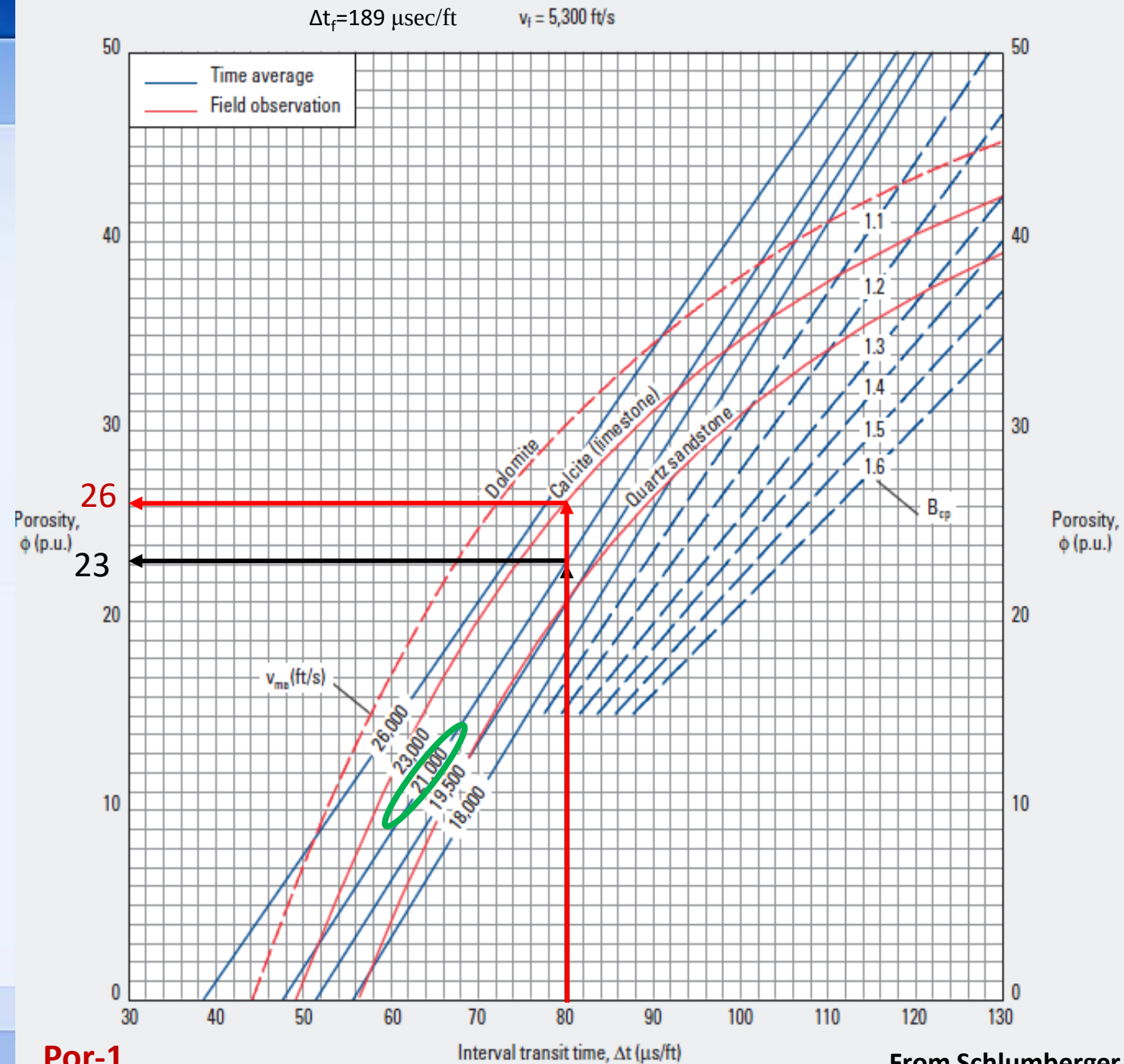
Example

Assume Δt log is 80 $\mu\text{sec}/\text{ft}$ and matrix is Limestone:

$$\phi_s = \frac{\Delta t - \Delta t_{ma}}{\Delta t_f - \Delta t_{ma}}$$

$$\phi_s = \frac{80 - 47.5}{189 - 47.5}$$

$$\phi_s = 22.9\%$$



Sonic Porosity in Unconsolidated Formations

- Unconsolidated formations exhibit travel times longer than Wyllie time-average equation.
- It can be handled by compaction factor B_{cp} .
- B_{cp} is a value greater than unity and can be obtained from transit time in adjacent shale formations.

$$\phi_s = \frac{\Delta t - \Delta t_{ma}}{\Delta t_f - \Delta t_{ma}} \times \frac{1}{B_{cp}}$$

$$B_{cp} = \frac{\Delta t_{sh}}{100}$$

Δt in adjacent shale

Sonic Log

Example

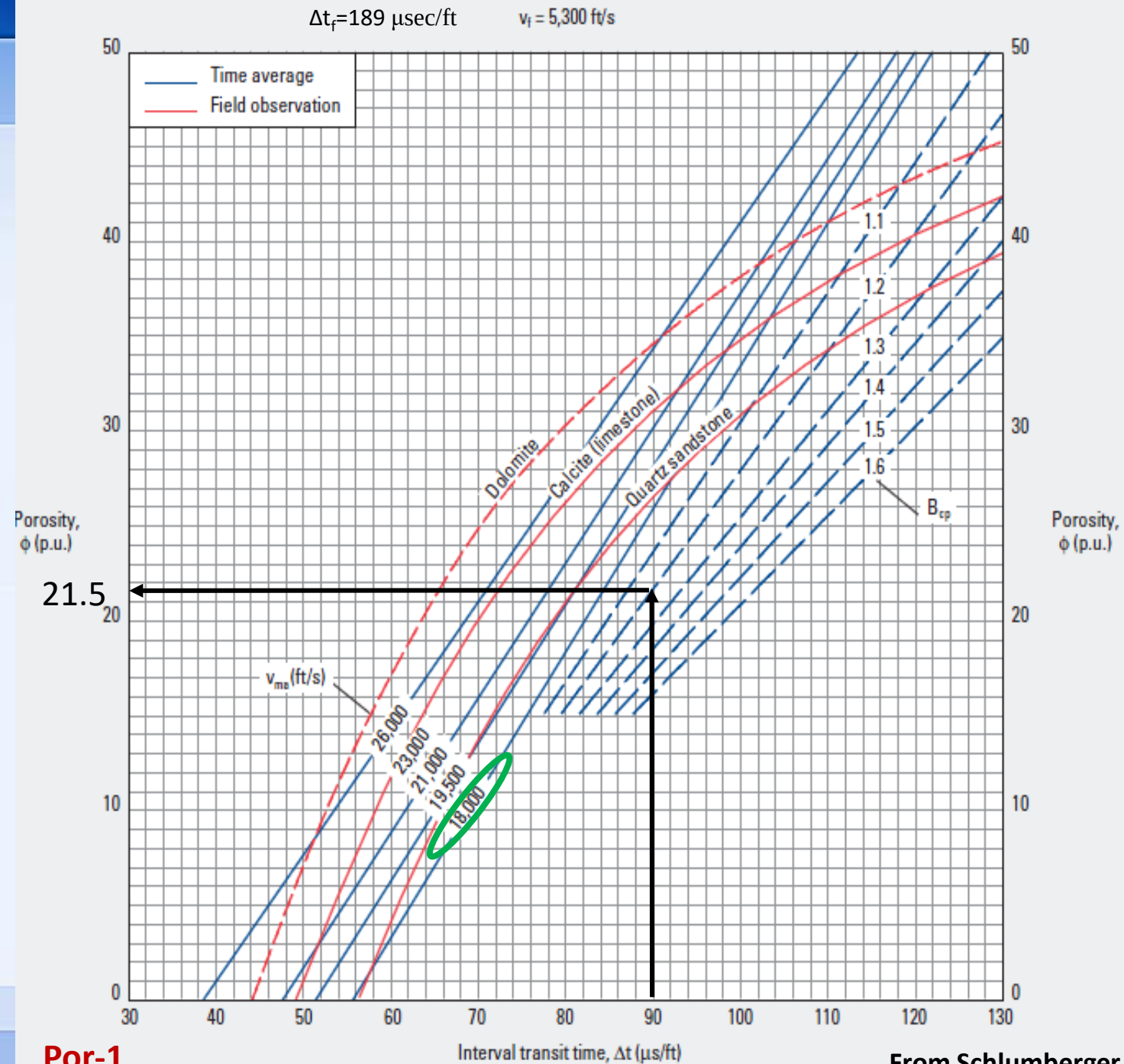
Assume Δt log is 90 $\mu\text{sec}/\text{ft}$ and matrix is sandstone.

Δt of shale in neighbor formation is 120 $\mu\text{sec}/\text{ft}$.

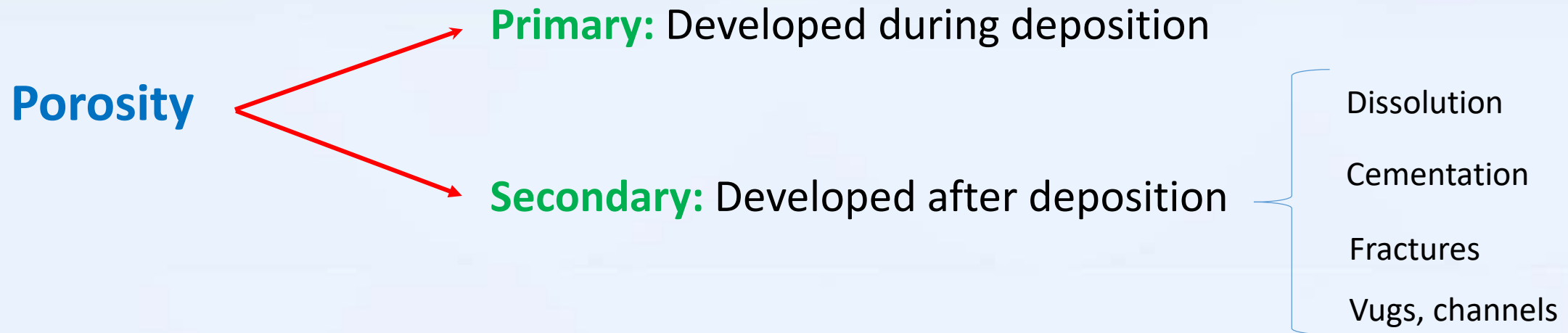
$$\phi_s = \frac{\Delta t - \Delta t_{ma}}{\Delta t_f - \Delta t_{ma}} \times \frac{1}{B_{cp}}$$

$$\phi_s = \frac{90 - 55.6}{189 - 55.6} \times \frac{100}{120}$$

$$\phi_s = 21.5\%$$



Secondary Porosity from Sonic Log



- Sonic tool is **Insensitive** to secondary porosity and ONLY detects primary porosity.
- Combination of other porosity tools (Neutron &/or Density) with sonic porosity tools can result in secondary porosity estimation.

$$\phi_{sec.} = \phi_{N,D} - \phi_s$$

Mechanical Properties from Sonic

Shear Modulus

$$\mu = \rho_b V_s^2$$

Young's Modulus

$$E = \frac{\rho_b V_s^2 (3V_c^2 - 4V_s^2)}{V_c^2 - V_s^2}$$

ρ_{ma} : Bulk density(from density log)

V_c : Compression wave velocity

V_s : Shear wave velocity

Bulk Modulus

$$B = \rho_b (V_c^2 - \frac{3}{4} V_s^2)$$

Poisson's Ratio

$$v = \frac{(V_c^2 - 2V_s^2)}{2(V_c^2 - V_s^2)}$$

P_p : Pore pressure

P_o : Overburden pressure

α : Constant (Appx. 0.5)

Formation Fracture Pressure:

$$P_f = \frac{2v}{1-v} \times P_o + \alpha \frac{1-3v}{1-v} \times P_p$$

R_{wa} as HC Indicator

Archie's Law:

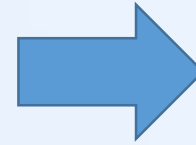
$$S_w = \sqrt[n]{F \frac{R_w}{R_t}}$$

From Sonic Log:

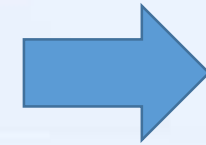
$$F = \frac{a}{\phi_s^m}$$

Assume:

$$R_{wa} = \frac{R_t}{F}$$



$$S_w = \sqrt[n]{\frac{R_w}{R_{wa}}}$$

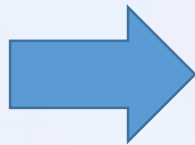


$$\frac{R_w}{R_{wa}} \leq 1$$

Always:

$$S_w \leq 1$$

$$\frac{R_w}{R_{wa}} \leq 1$$



$$R_w \leq R_{wa}$$



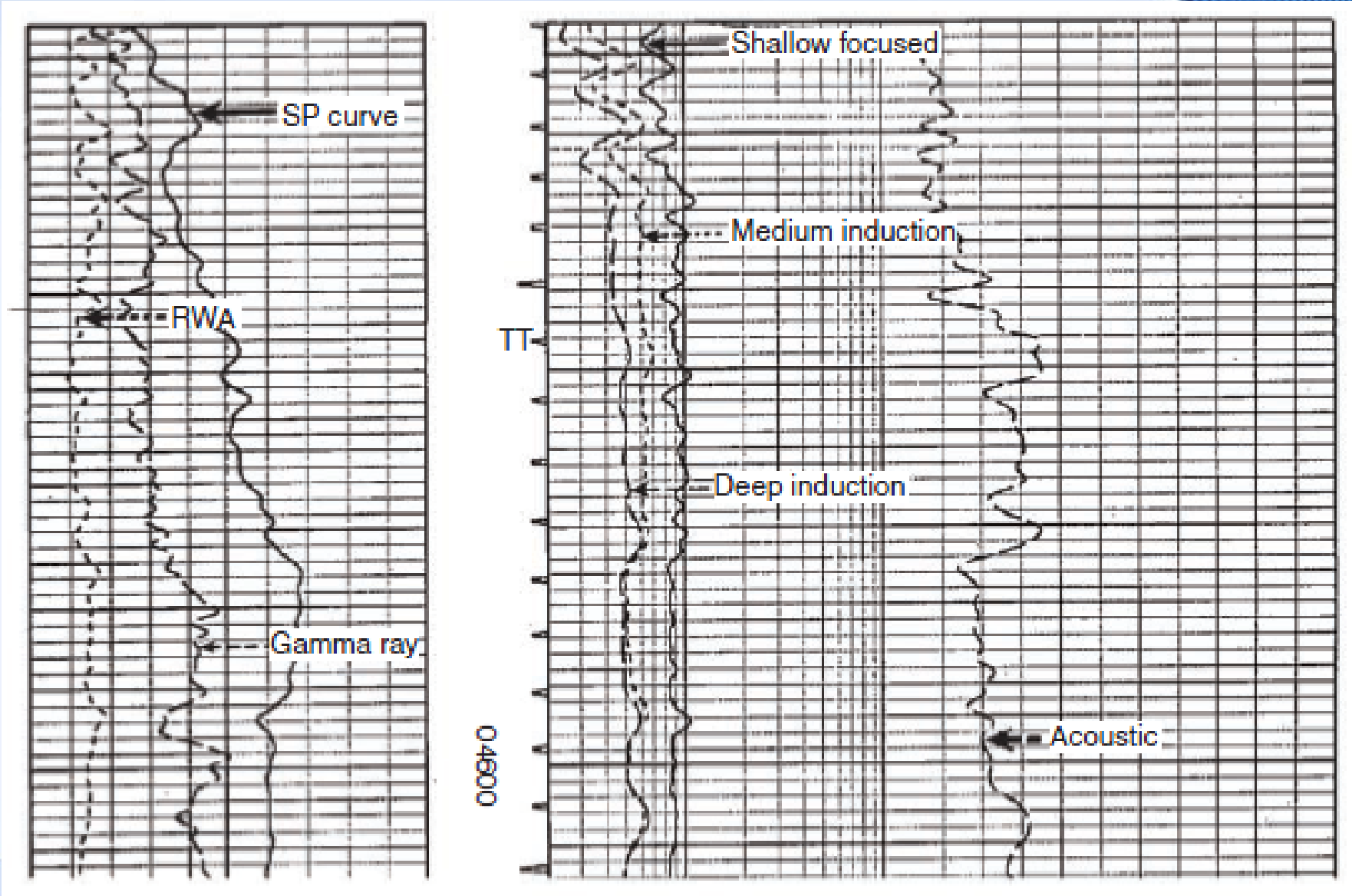
$$R_w < R_{wa}$$

Min value of R_{wa} on the log

$$(R_{wa})_{min} = R_w \text{ In Water zone}$$

In HC zone

R_{wa} Log Curve



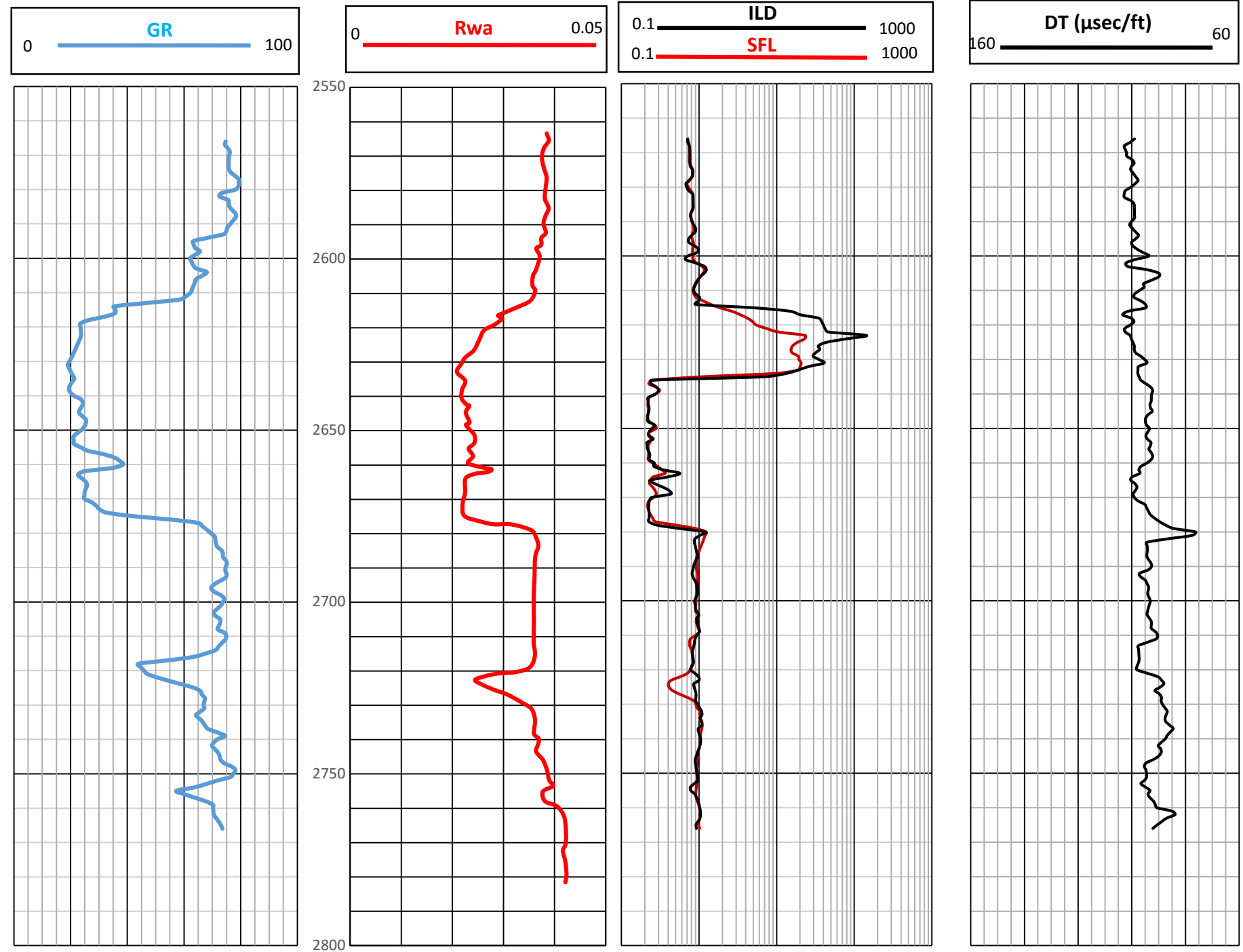
Sonic Log

Example

Any possible reservoir?

Any Water Zone?

Rw?



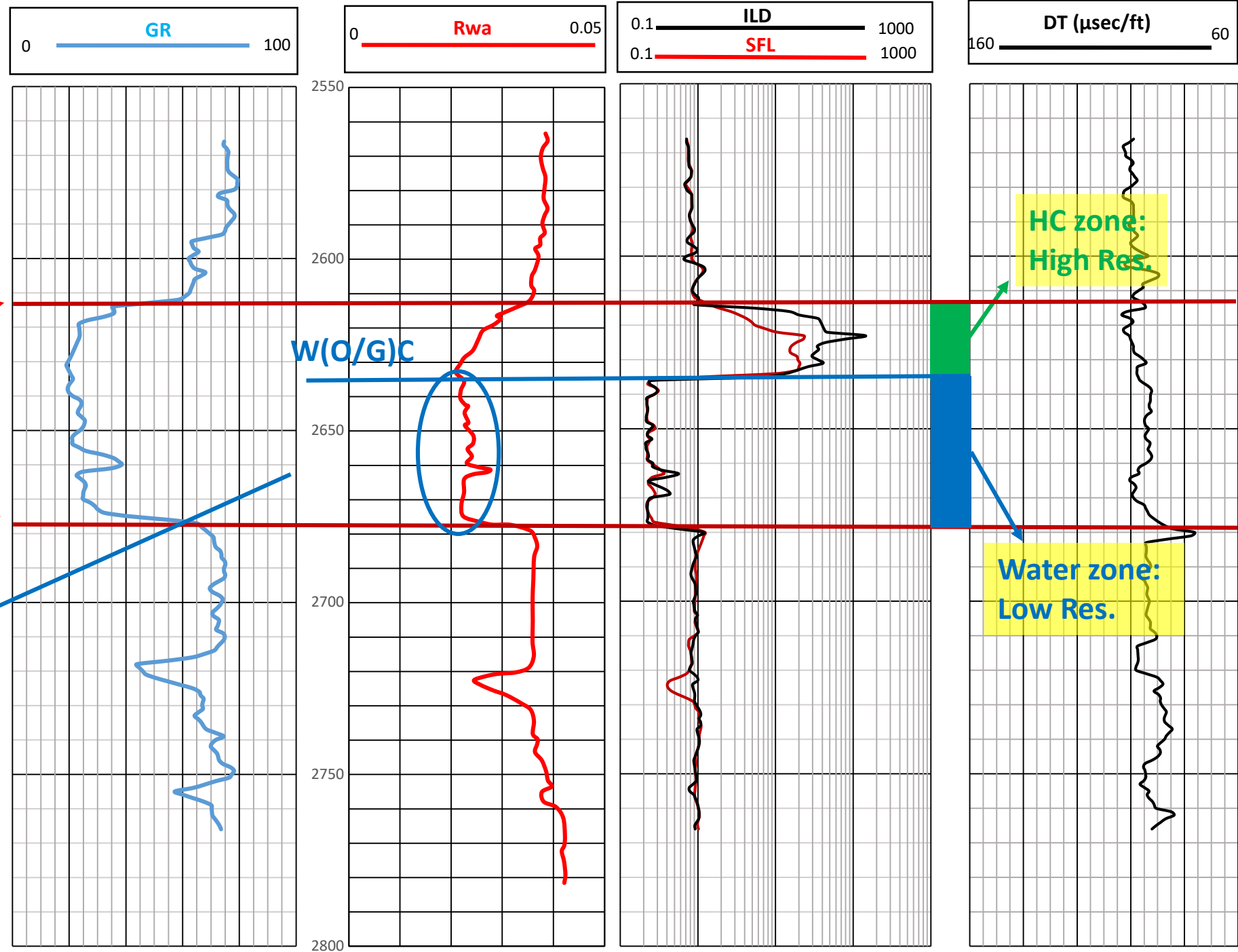
Sonic Log

Example

Permeable zone:

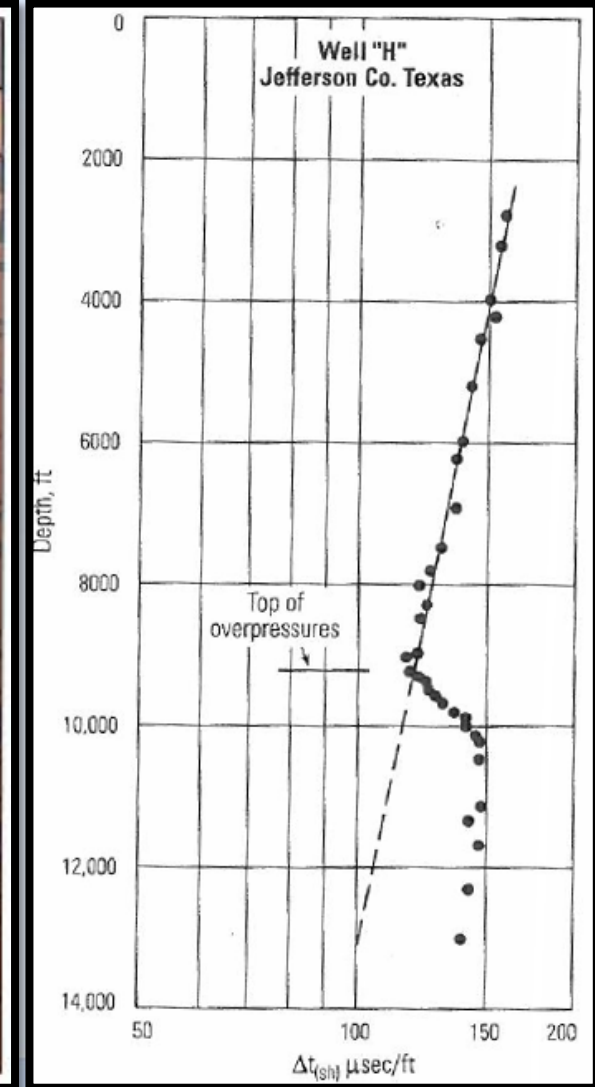
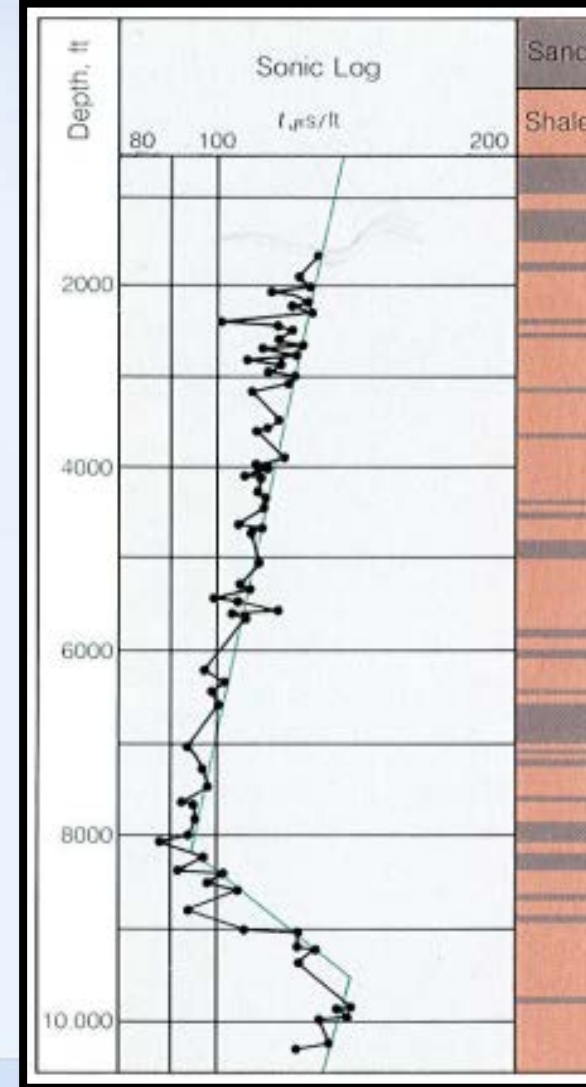
- Low GR
- Separation between SFL & ILD

$$(R_{wa})_{min} = R_w$$

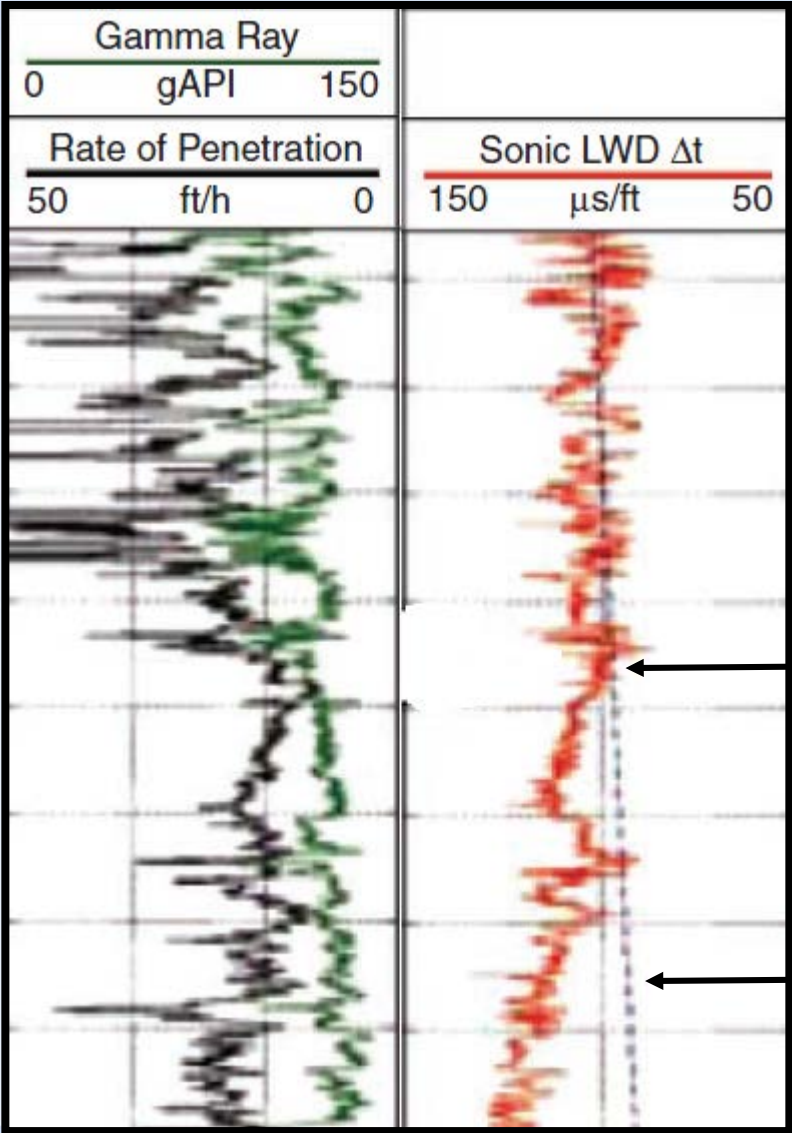


Over-Pressured Formations

- The deeper a formation is, the more compact it becomes (overburden pressure increase).
- The more compact the formation is, the less transit time is recorded.
- The transit time on a logarithmic scale vs. depth on a linear scale, should show a straight line as compaction trend.
- If there is a break in the compaction trend with depth to higher transit times with no change in lithology, it might indicate the top of an over-pressured zone.
- This behavior is common in shales.



Over-Pressured Shale

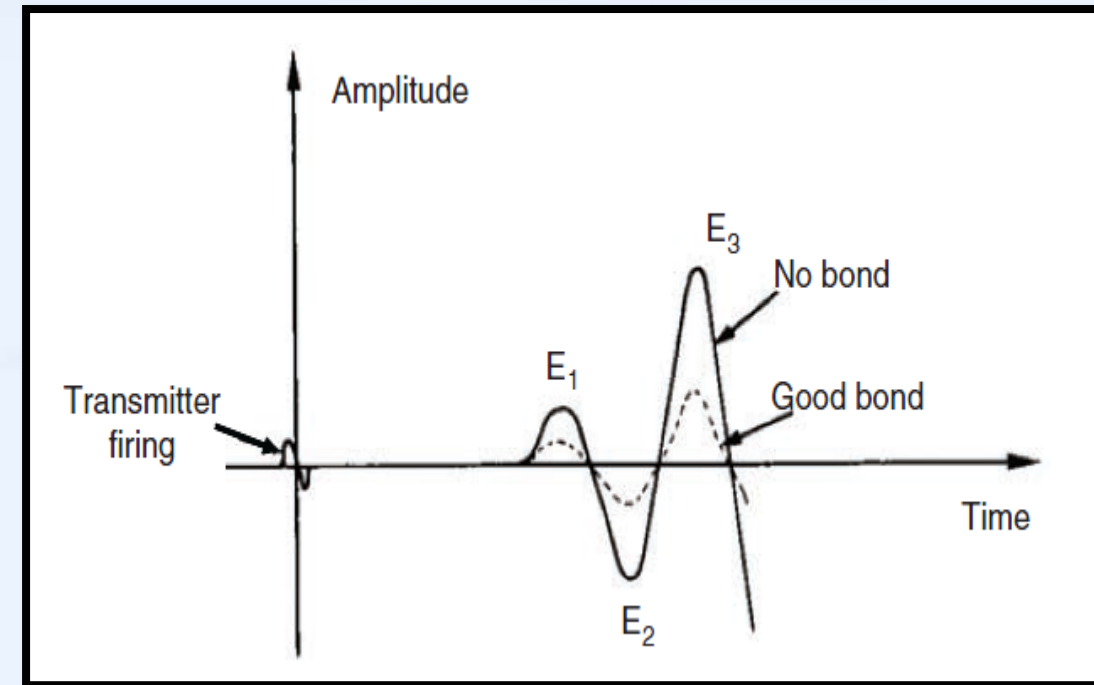


Onset of over-pressure

Compaction trend line

Cement Bond Log (CBL)

- ✓ A proper cement behind casing assures:
 - Casing is well supported.
 - Producing zones do not contaminate water bearing zones
 - No surface fluid leakage
- ✓ CBL is similar to BHC.
- ✓ It measure the amplitude of the first arrival waves.
- ✓ The amplitude indicates the quality of the bonding.
- ✓ CBL is usually accompanied by wavetrain display of variable density log (VDL).
- ✓ A good cement bond exists when later wave arrivals on VDL are strong.



Bateman, 2012

Cement Bond Log (CBL)

Bad Cementing (Free Pipe):

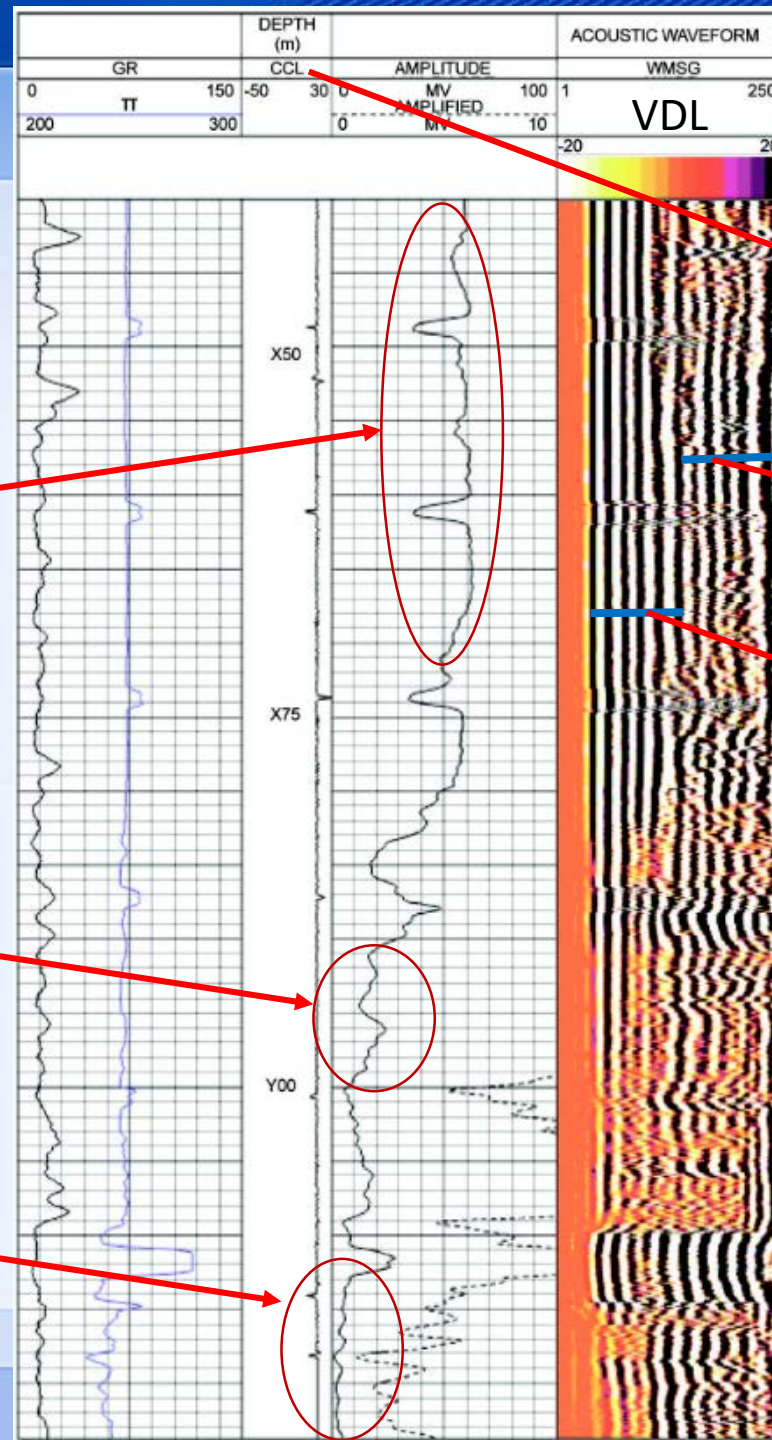
High Amplitude
Weak VDL (Formation)
V shape @ CSG collar

Partial Cementing:

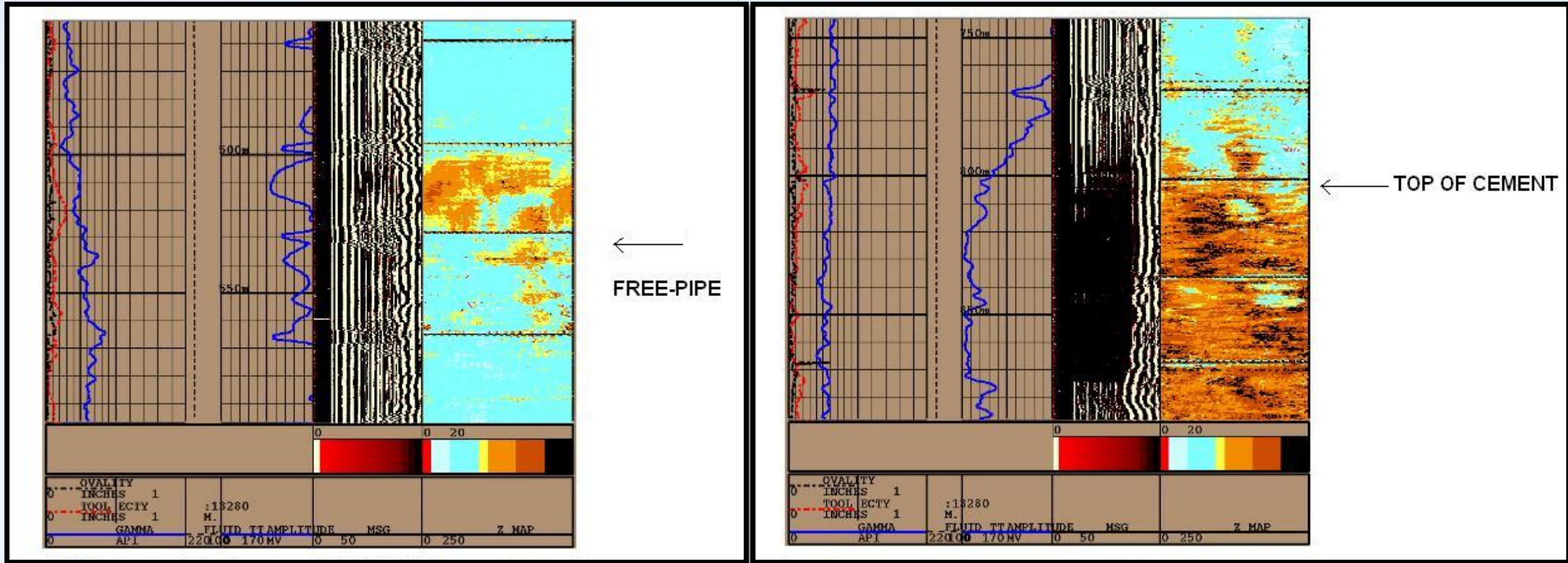
Moderate Amplitude
Moderate VDL (Formation)

Good Cementing:

Low Amplitude
Strong VDL (Formation)

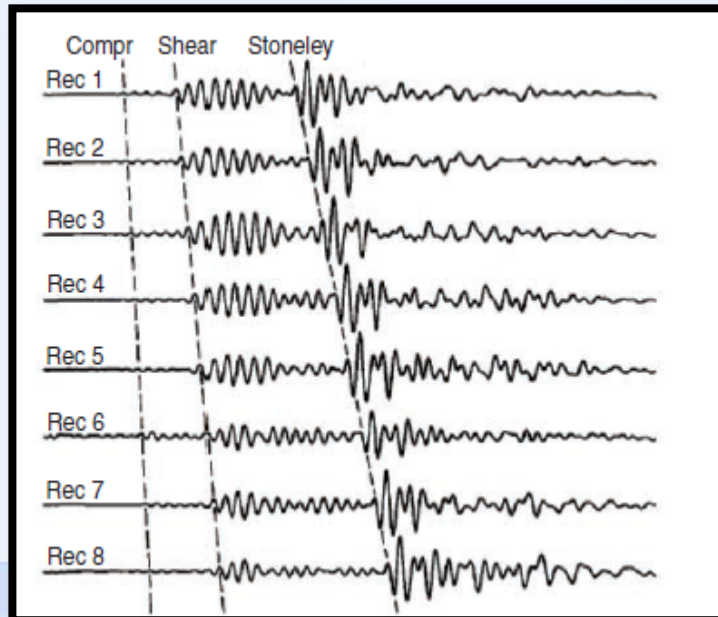


Cement Bond Log (CBL)

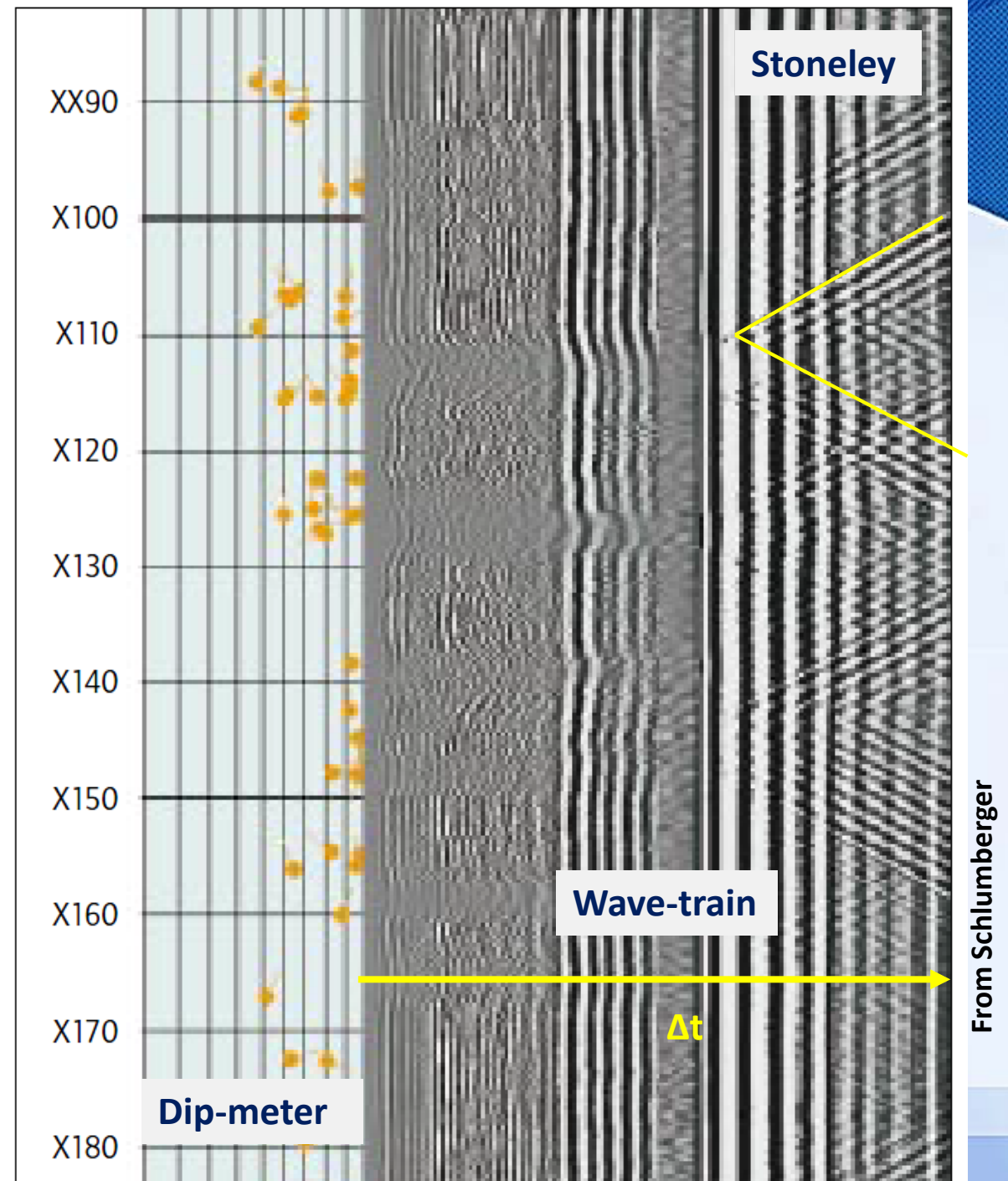


Fracture Detection

- Fracture causes delay (due to attenuation) on wave-train of compression, shear and Stoneley waves.
- Fracture causes a “chevron pattern” (V shape) effect on Stoneley waves.



Wave-train



Sonic Log

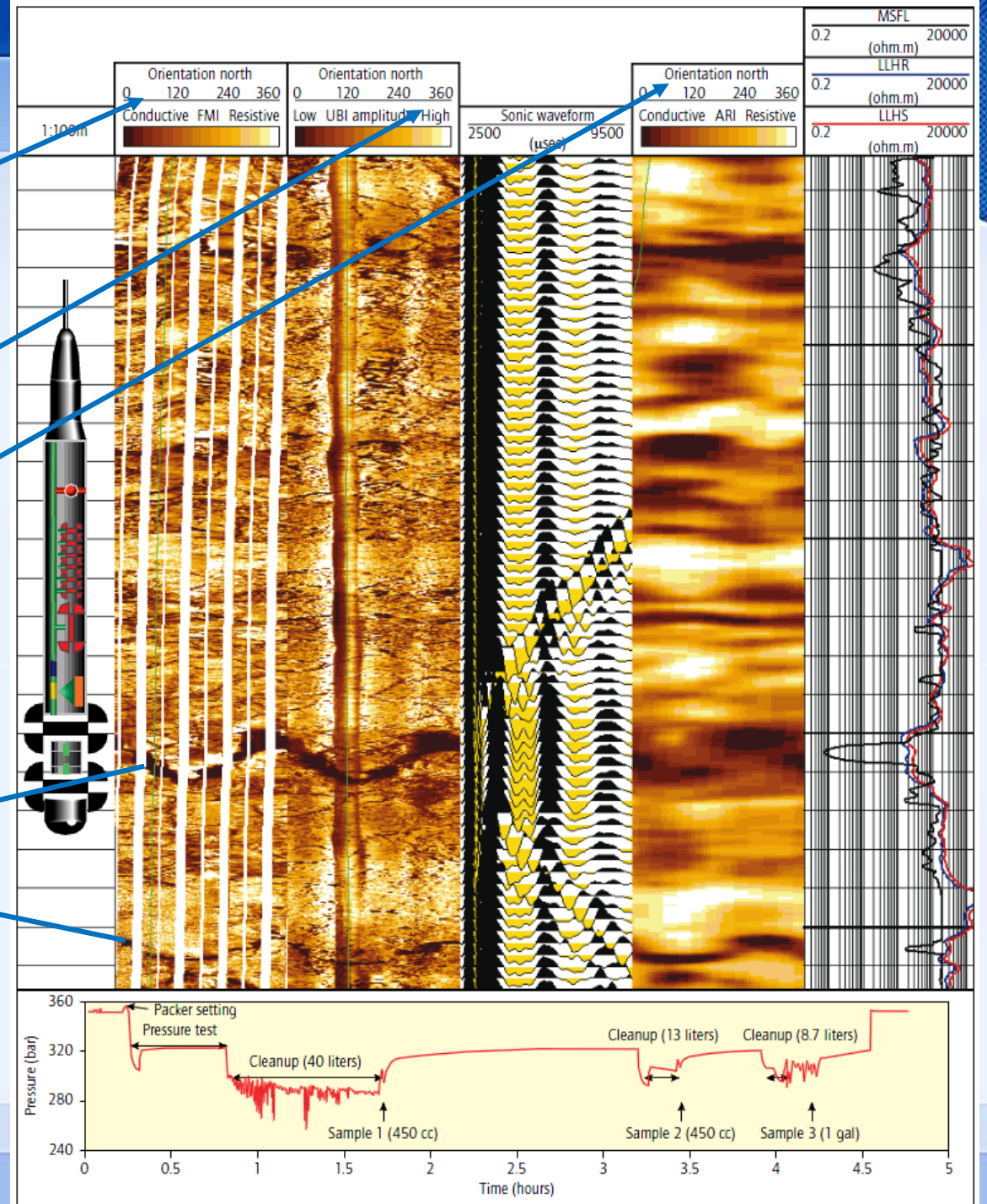
Fracture Detection

Fullbore Formation MicroImager (FMI)

Ultrasonic Borehole Imager (UBI)

Azimuthal Resistivity Image (ARI)

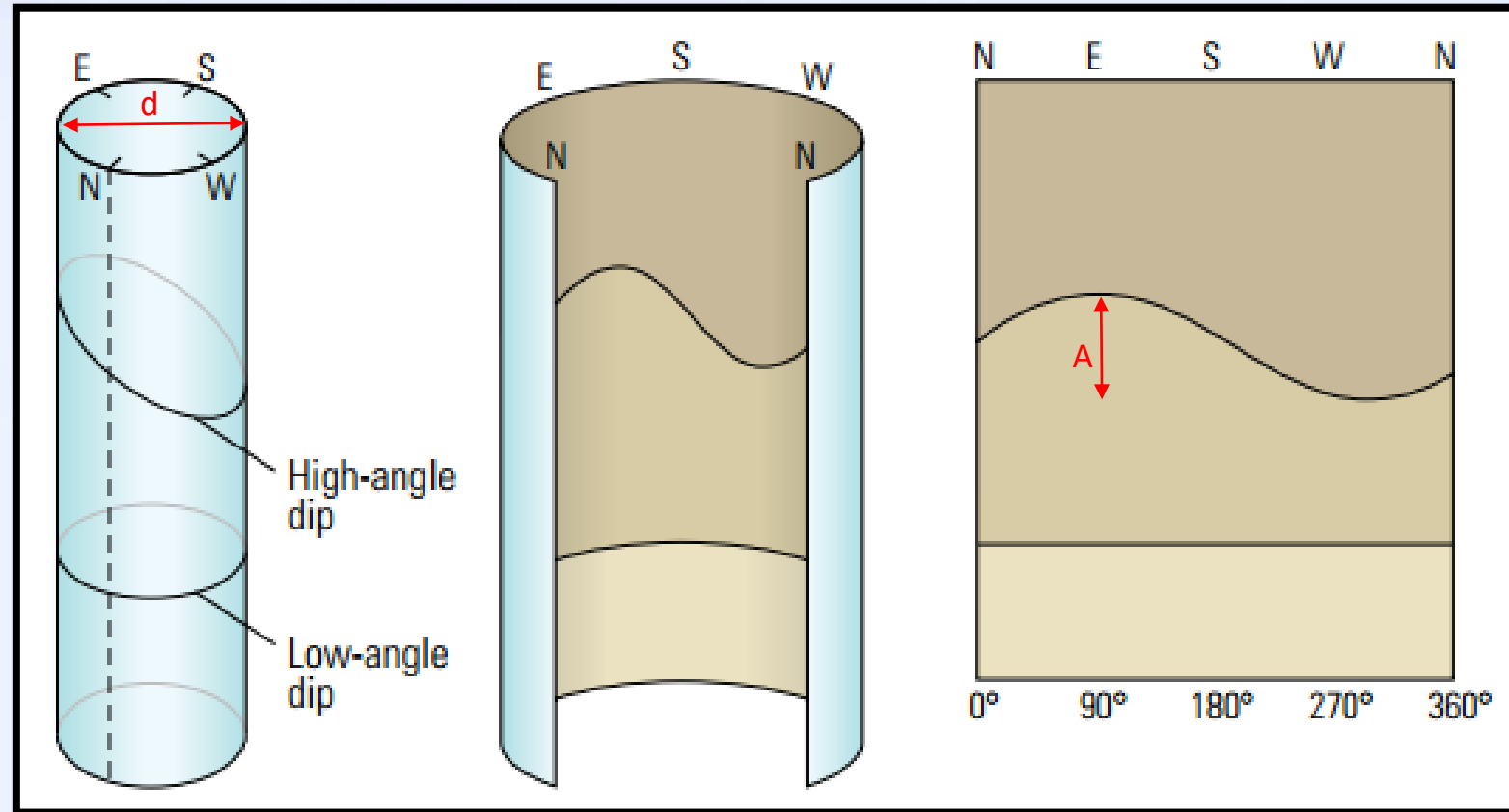
Fracture



From Schlumberger

Fracture Quantification

- A dipping plane becomes sinusoid wave on projection (3D to 2D).
- Dip can be calculated from amplitude, A , and borehole diameter, d .
- Azimuth can be read directly from the sinusoid.

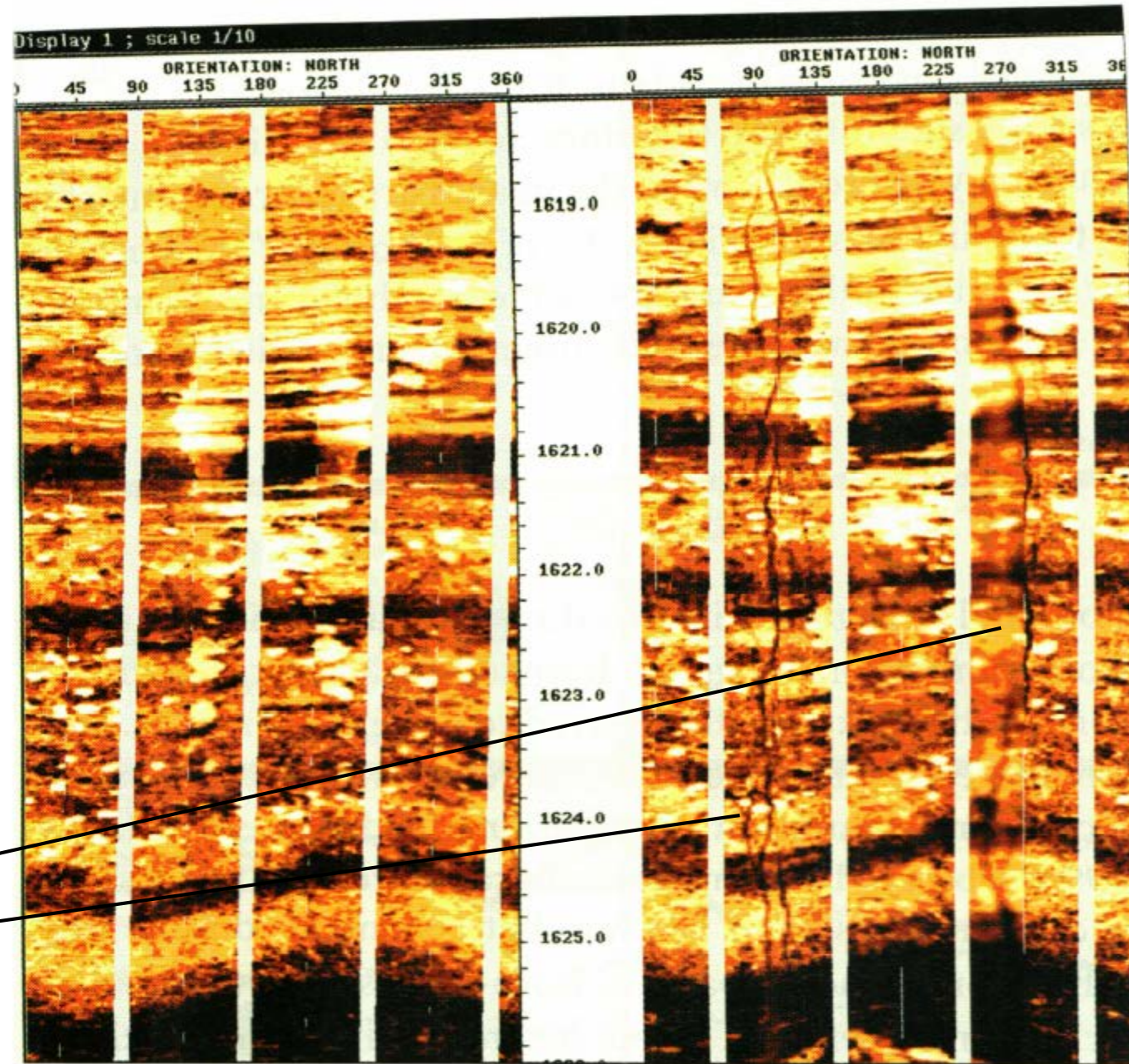


From Schlumberger

FMI Application in Fractures

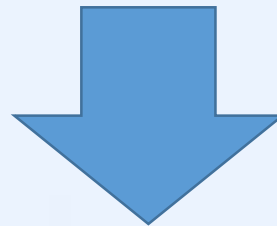
- Qualifies the fracture
 - ✓ Azimuth
 - ✓ Dip
 - ✓ Aperture
- Type of fracture (natural or induced)

Induced fractures (Dip=90°) after hydraulic fracturing job.



Sonic Porosity Limitations

- ❑ To estimate porosity the matrix lithology must to be known.
- ❑ It is insensitive to secondary porosity and cannot detect it.
- ❑ Requires compaction correction.
- ❑ Transition from one lithology to other one is not easily evident.
- ❑ Gas bearing zones are not easily detectable.



Replaced with Density-Neutron logs to overcome these problems

Summary

- ☐ Can be used for mechanical properties, porosity, fracture studies.
- ☐ Requires correction for borehole, mud and compaction.
- ☐ R_{wa} method.
- ☐ Identifying over-pressured zones

Useful Charts

o Por-1