Acoustics and Ultrasonics for Downhole Oil and Gas Logging

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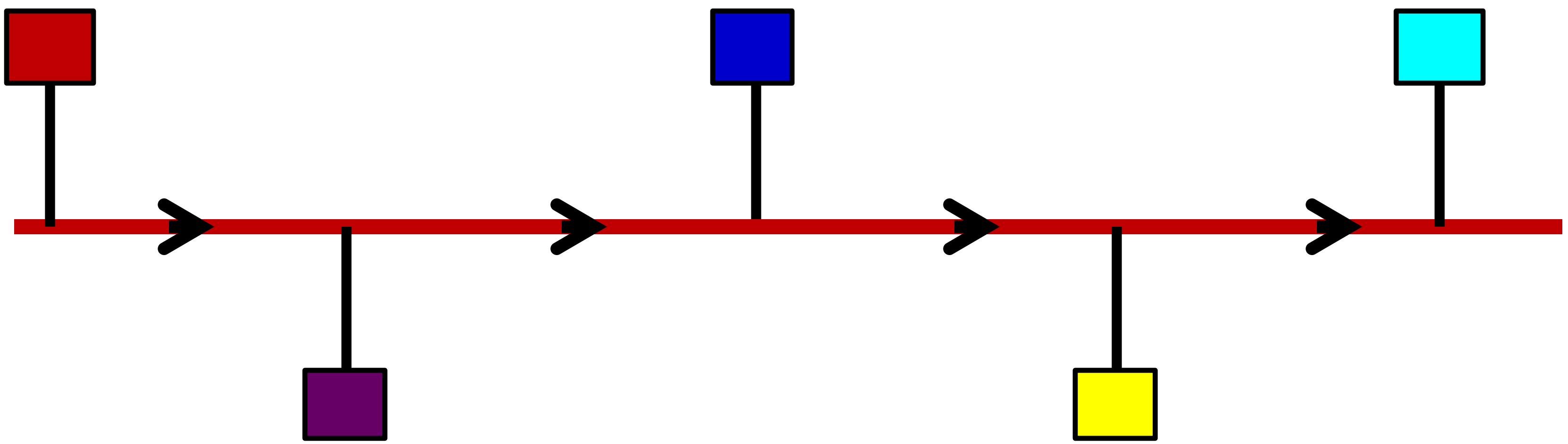
Presentation Roadmap

- Method of Well Drilling
- Method of Well Completion
- Questions



- Sonic Formation P-Wave and S-Wave Logging
- Ultrasonic Casing Thickness Inspection and Cement Bond Evaluation

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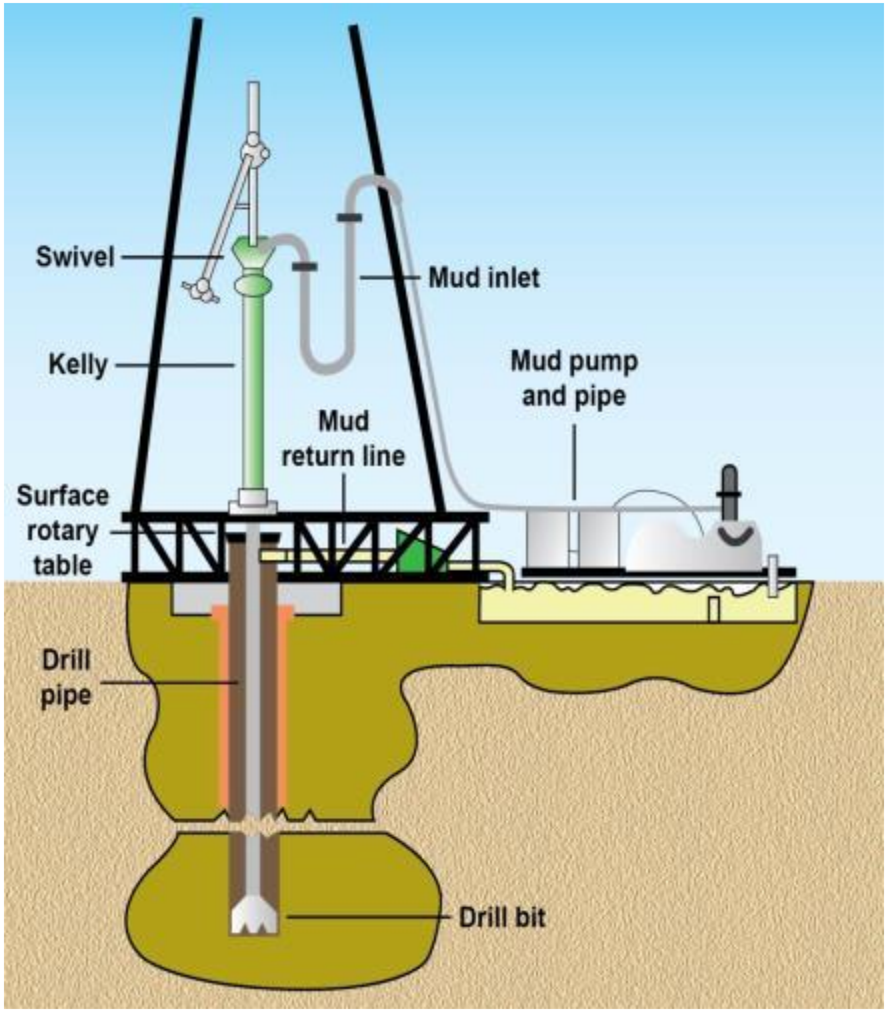
Well Drilling Method

Equipment and process

Oil and Gas Wells
Well drilling process

- Upper pipe section rotated,
  lower pipe sections,
  drill bit rotated
- Closed-loop mud circulated
  - From surface down center of the pipe and out the jets in the drill bit
  - Return to surface the outside pipe
  - Suspended cuttings carried to the surface
  - Mud cleaned and returned to pit
- New pipe sections added as depth increases



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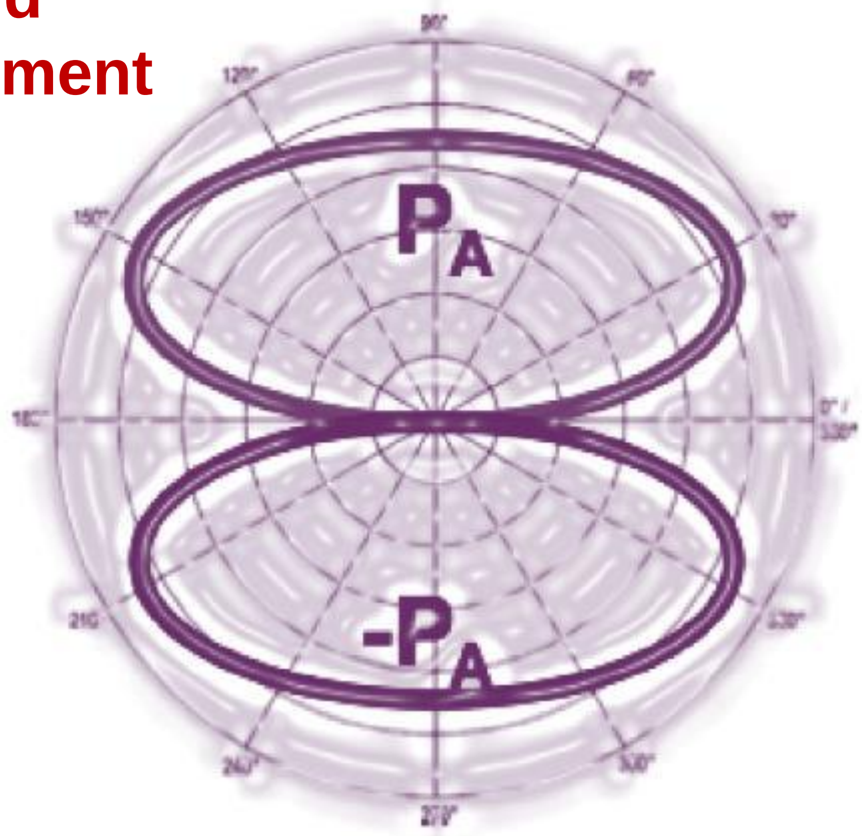
Sonic Open Hole Wireline Logging

Formation Compressional and Shear Sound Speed Measurement



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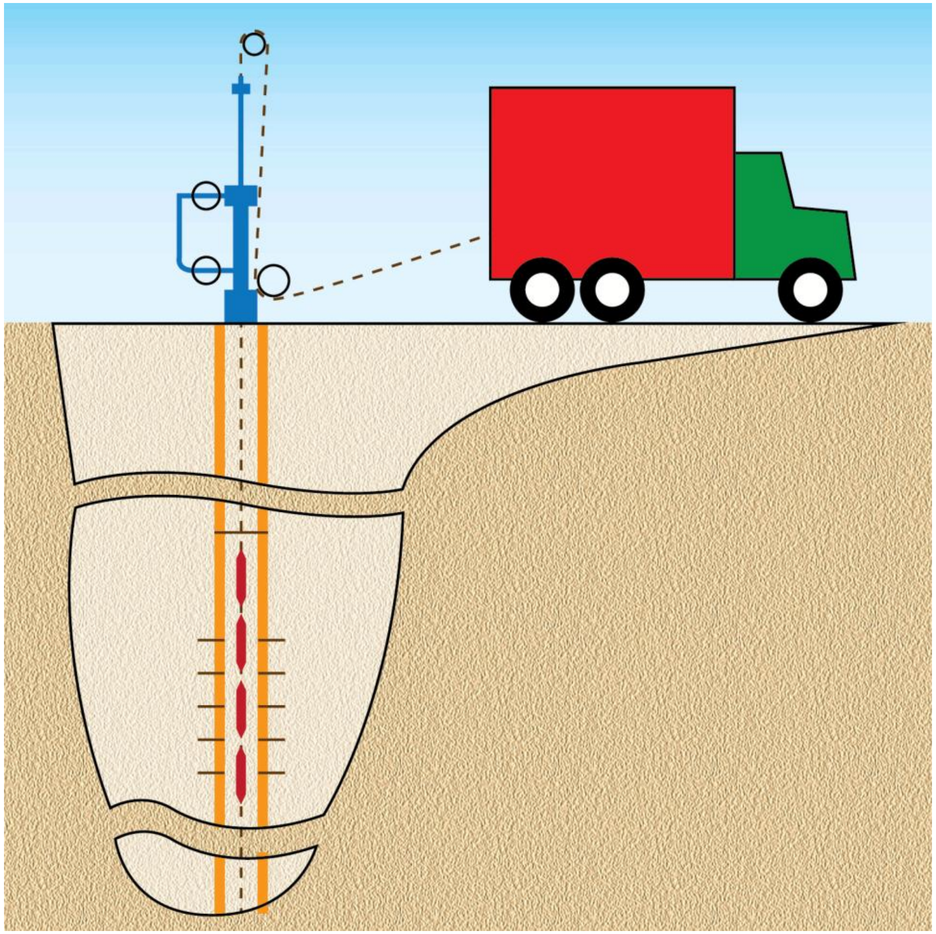
Open-Hole Wireline Logging

Evaluating the Drilled Formation

- Wireline tools
  - 5 cm to 15 cm in diameter
  - 3-6 meters length
  - 50 to 250 Kg weight
- Tool string
  - Array of tools screwed together
- Cable
  - Lowers and retrieves tool string
  - Provides tool power
  - Sends tool data to surface 30 kB



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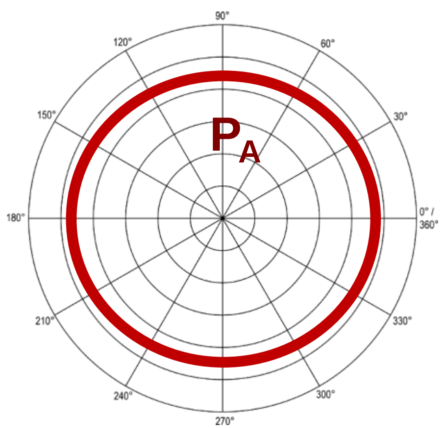
Open-Hole Wireline Tools for Formation Evaluation
Resistivity, Density, Porosity, and Acoustic

- Resistivity
  - Formation: containing salt water in pores conducts
  - Formation: containing hydrocarbons in pores insulates
- Nuclear (gamma) density
  - Formation: 1.7 g/cc to 4.0 g/cc
- Nuclear (neutron) porosity
  - Formation: 0% porous to 40% porous
- Sound speed
  - Formation v_L: 2000 m/sec to 5000 m/sec
  - Formation v_S: 1200 m/sec to 3000 m/sec

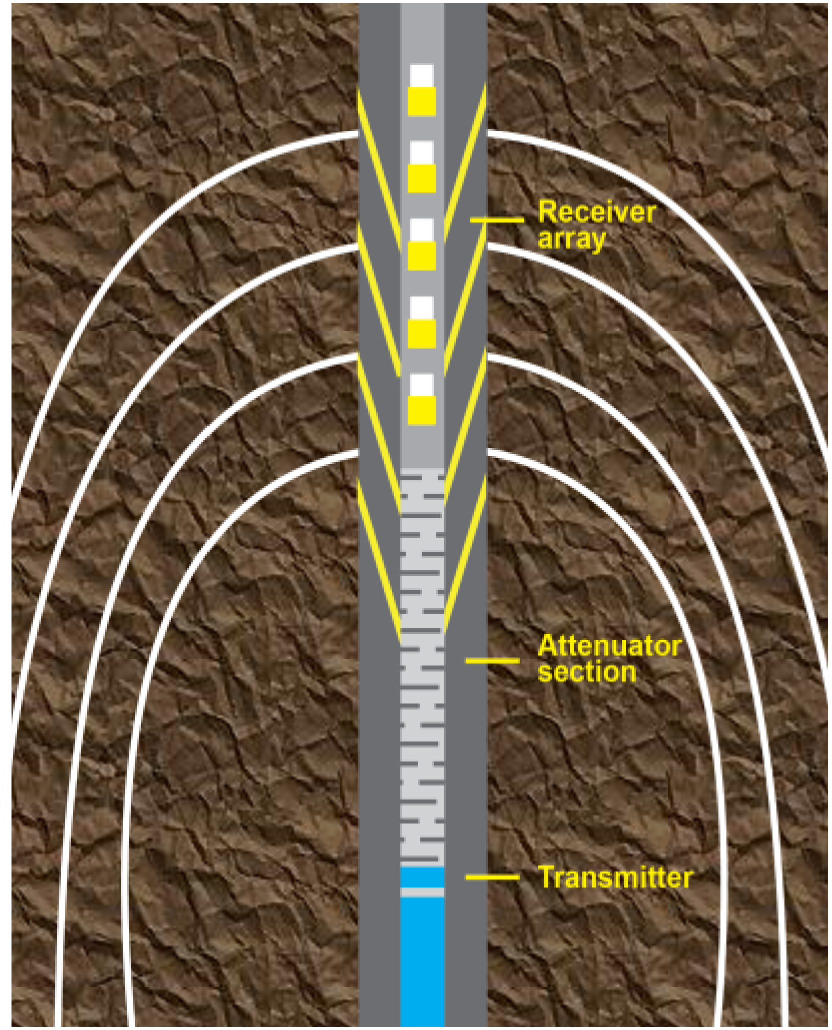
Sonic Open-Hole Wireline Tools

Measure Formation Compressional and Shear Velocity

- Monopole source (<20 KHz)



- Attenuator
- Vertical receivers arrays
  - 6-8 vertical elements
  - 3m to 5m
  - 0^{o}, 90^{o}, 180^{o}, 270^{o}



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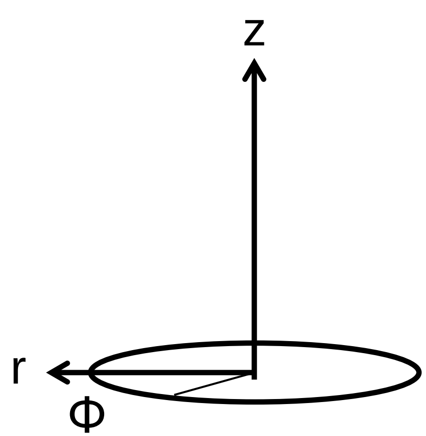
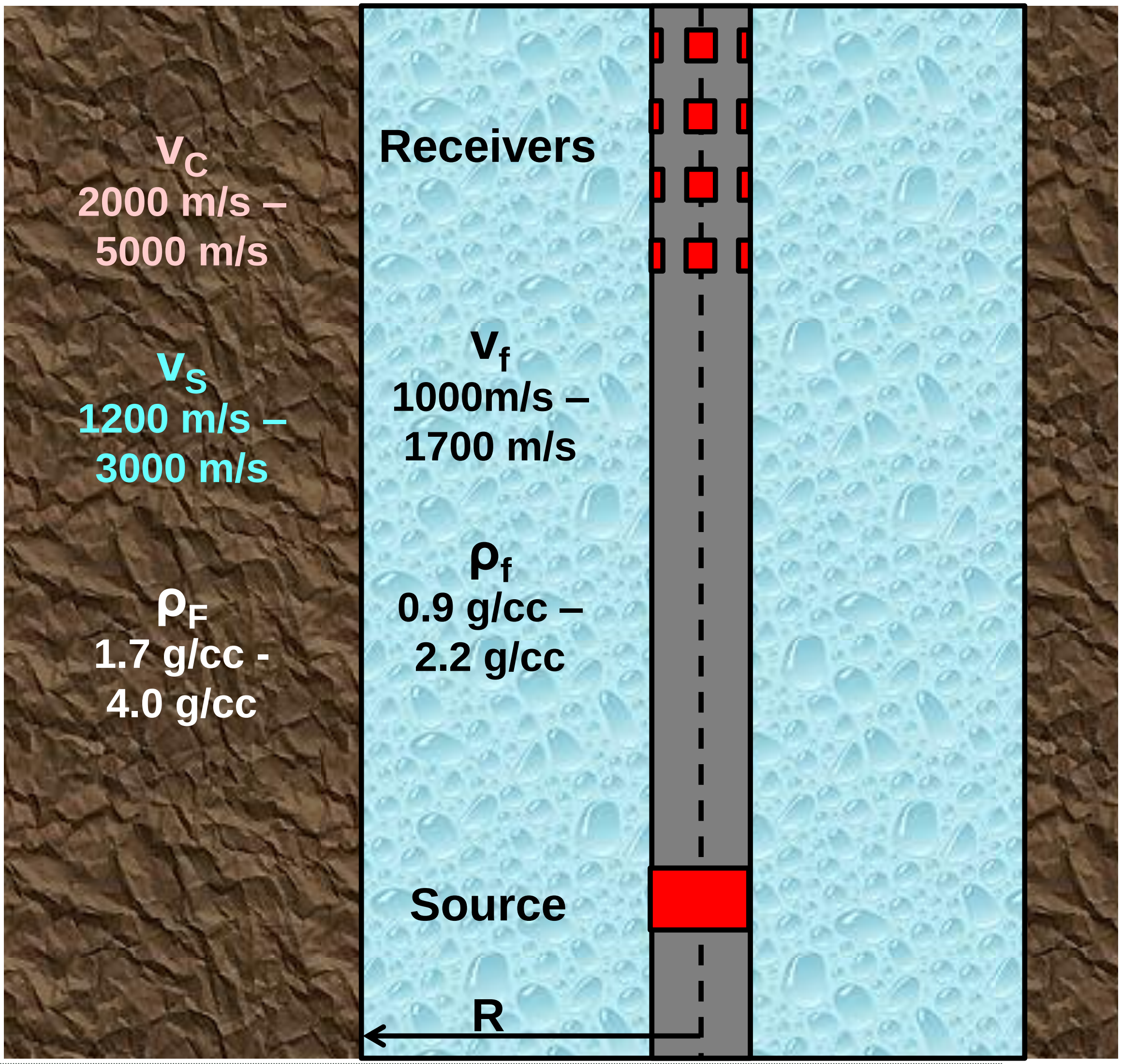
Sonic Open-Hole Wireline Tools

Media and Coordinate Systems

- Fluid-filled borehole radius R
- Elastic formation
- Cylindrical coordinates (r,ϕ,z)



- Monopole source $r = R_0$, $z = 0$, no Φ dependence



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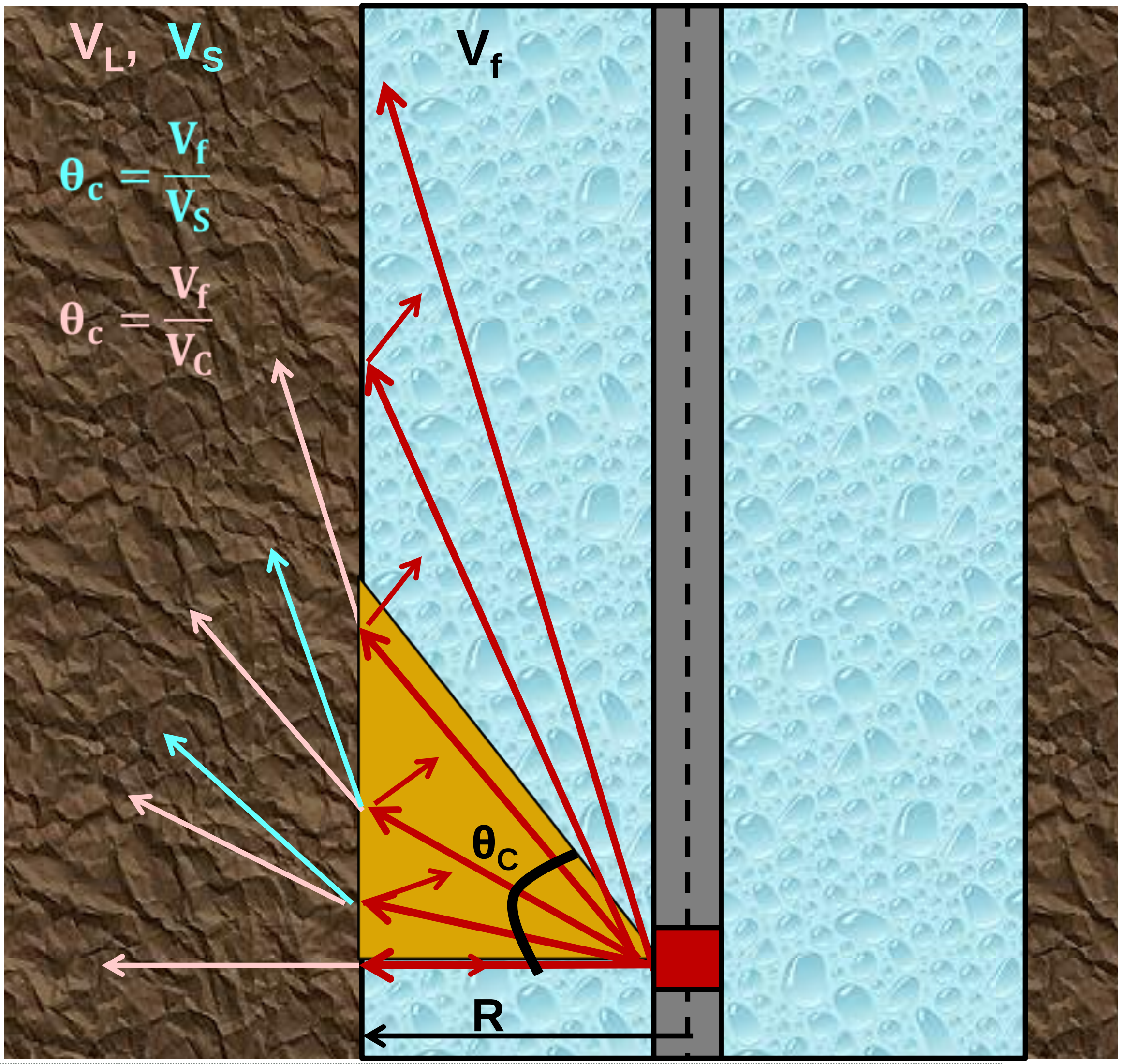
Sonic Wireline Tools

Imperfect Cylindrical Waveguide

- Non-refracted angles
  $\theta_i < \theta_c$



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Sonic Open-Hole Wireline Tools

Displacement Potentials

elastic formation

potential Φ_F

$$\Phi_F = B_1\,(\,)e^{i(\kappa z-\omega t)} + B_2\,(\,)e^{i(\kappa z-\omega t)}$$

$$k_L = \frac{\omega}{v_L} \qquad k_S = \frac{\omega}{v_S}$$

$$k_L{}^2 = m_2{}^2 + \kappa^2$$
$$k_S{}^2 = m_3{}^2 + \kappa^2$$

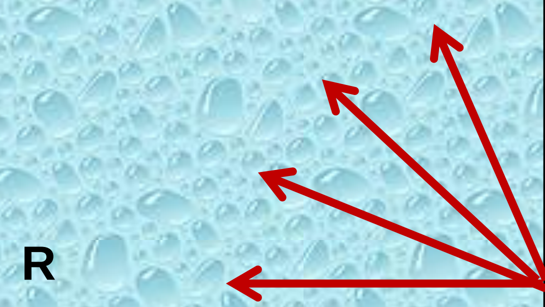
borehole fluid

potential Φ_f

$$\Phi_f = A_1(\,)e^{i(\kappa z-\omega t)} + A_2\,(\,)e^{i(\kappa z-\omega t)}$$

$$k_f = \frac{\omega}{v_f}$$

$$k_f{}^2 = m_1{}^2 + \kappa^2$$



tool

potential Φ_T

$$\Phi_T = C_1(\,)e^{i(\kappa z-\omega t)} + C_2\,(\,)e^{i(\kappa z-\omega t)}$$

$$k_T = \frac{\omega}{v_f} \qquad k_T = \frac{\omega}{v_f}$$

$$k_{TL}{}^2 = m_4{}^2 + \kappa^2$$
$$k_{TS}{}^2 = m_5{}^2 + \kappa^2$$

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Sonic Wireline Tools

Relating A_1, A_2, B_1, B_2, C_1, C_2

(1) Use Hooke's Law to get stress and strains

(2) Use boundary conditions

Borehole Surface

$$u_r(R) = u_{rf}(R)$$

$$\sigma_{rr}(R) = P_f(R)$$

$$\sigma_{rz}(R) = 0, \qquad eliminates\ B_2$$

Tool Surface

$$u_r(R_0) = u_{rf}(R_0)$$

$$\sigma_{rr}(R_0) = P_f(R_0)$$

$$\sigma_{rz}(R_0) = 0, \qquad eliminates\ C_2$$

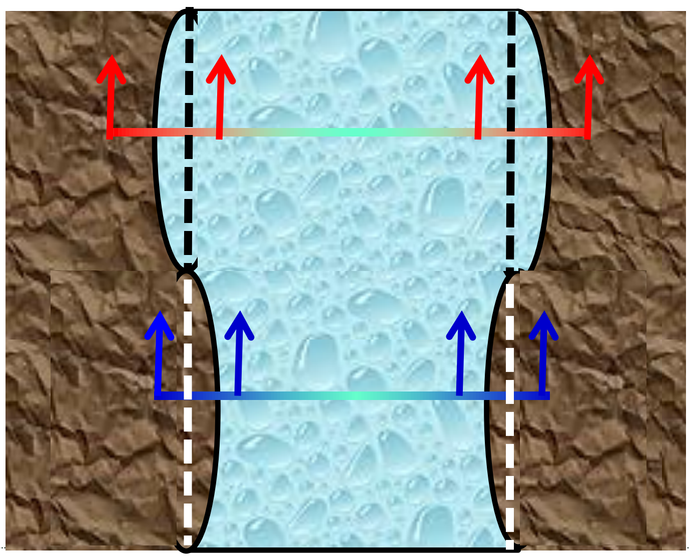
Sonic Open-Hole Wireline Tools

Dispersion Relations

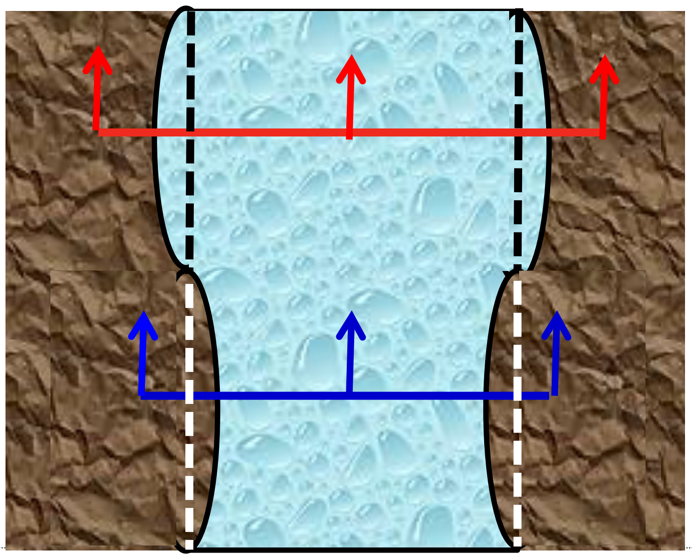
$$\begin{bmatrix} \theta_{11} & \theta_{12} & \theta_{13} & \theta_{14} \\ \theta_{21} & \theta_{22} & \theta_{23} & \theta_{24} \\ \theta_{31} & \theta_{32} & \theta_{33} & \theta_{34} \\ \theta_{41} & \theta_{42} & \theta_{43} & \theta_{44} \end{bmatrix} \begin{bmatrix} A_1 \\ B_1 \\ A_2 \\ C_1 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} \qquad det[\theta_{ij}] = 0$$

Gives dispersion relations for two trapped modes

Stoneley Wave
Interface wave that decays from fluid-formation interface



Pseudo-Rayleigh Wave
Symmetric collective motion of borehole



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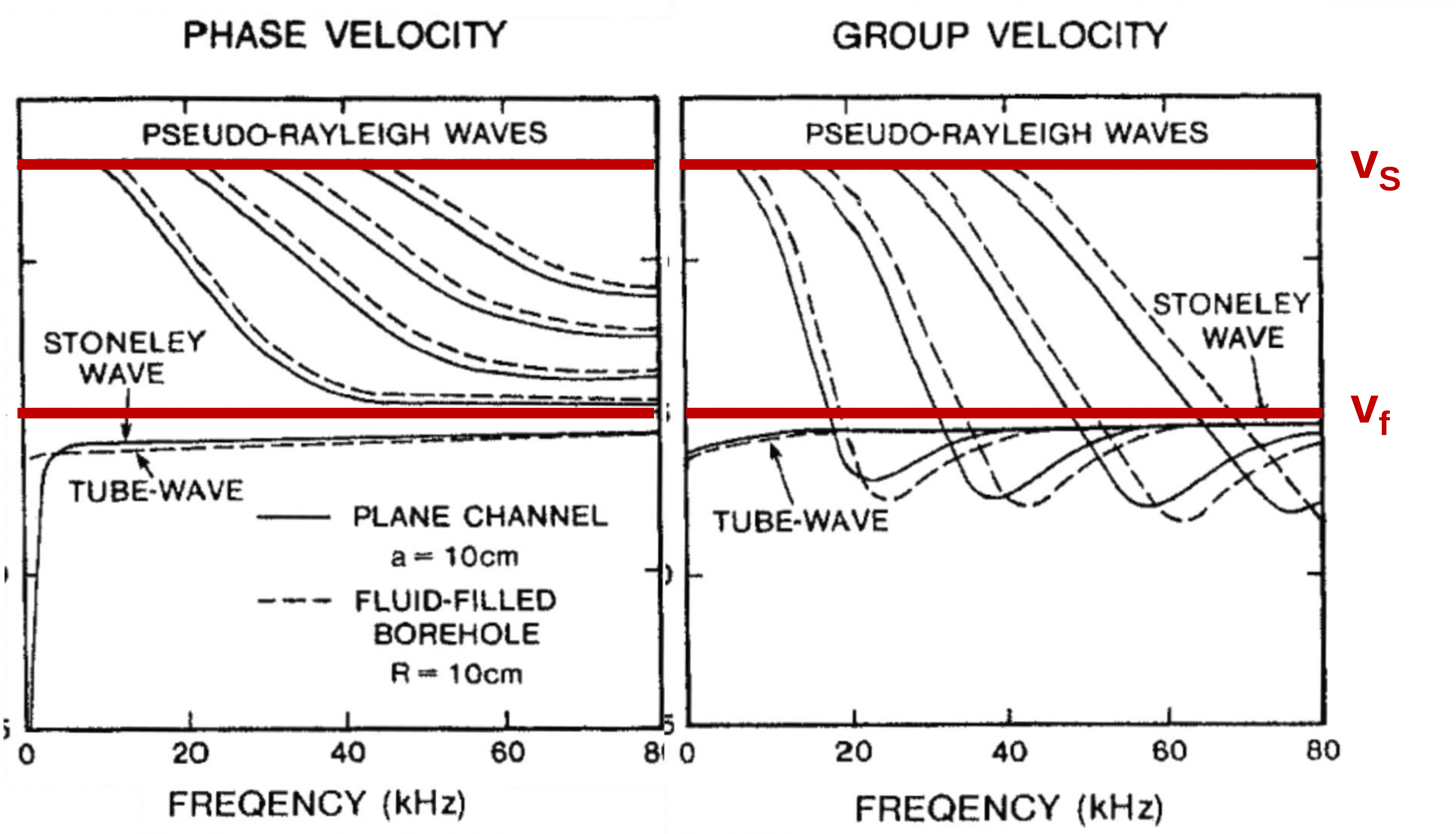
Sonic Open-Hole Wireline Tools

Stoneley and Pseudo-Rayleigh Dispersion Curves



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Sonic Open-Hole Wireline Tools

P(z,t) Synthetic Micro-Seismograms

$P(z,t) = integral\ \ of\, A_1\ and\ A_2\ over\ frequency\ \ \omega\ and\ wavenumber\ \kappa$

$Assume\ no\ tool\ is\ present,\ A_2 = 0\ as\ K_0 \rightarrow \infty\ as\ r \rightarrow 0$

$*Assume\ acoustic\ source\ is\ present\ and\ provides$
$radial\ displacement\, u_S = -mK_1(m_1R)e^{i(\kappa z-\omega t)}\, and$
$stress\ \sigma_S = -\rho_f K_0(m_1R)e^{i(\kappa z-\omega t)}\ \ at\ the\ borehole\ wall$

$$\begin{bmatrix} \theta_{11} & \theta_{12} \\ \theta_{21} & \theta_{22} \end{bmatrix} \begin{bmatrix} A_1 \\ B_2 \end{bmatrix} = \begin{bmatrix} -m_1K_1(m_1R) \\ -\rho_f K_0(m_1R) \end{bmatrix}$$

Sonic Open-Hole Wireline Tools

Synthetic Micro-Seismograms

$$P(z,t) = \textit{integral over frequency } \omega \textit{ and wavenumber } \kappa$$

$$P(z,t) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} S(\omega)\ A_1(\omega,\kappa)\ e^{i\kappa z}\, e^{-i\omega t} d\omega d\kappa$$

$$\textit{source functon,} \qquad S(\omega) = \left(\frac{\omega}{\omega_0}\right)^2 e^{-\left(\omega/\omega_0\right)^2}$$

$$A_1(\omega,\kappa) = \frac{gK_1(m_1R) - K_0(m_1R)}{gI_1(m_1R) + I_0(m_1R)}$$

$$g = \frac{m_1\rho_F}{m_2\rho_f}\left\{\left[\frac{2\kappa^2 v_S{}^2}{\omega^2}\right]\frac{K_0(m_2R)}{K_1(m_2R)} + \frac{2v_S{}^2 m_2 m_3}{\omega^2}\left[\frac{1}{m_3R} + \frac{2\kappa^2 v_S{}^2 K_0(m_3R)}{\omega^2 K_1(m_3R)}\right]\right\}$$

Singularities in integral produce solution P(z,t), trapped and leaky modes

Sonic Open-Hole Wireline Tools

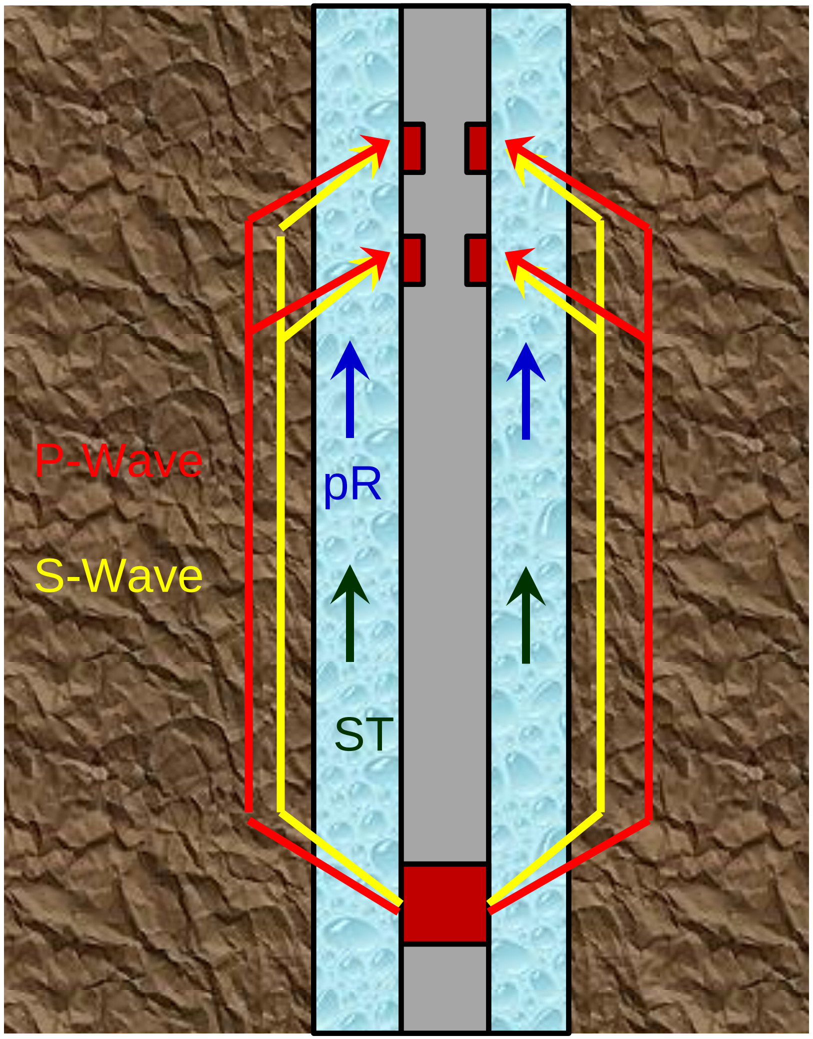
Four Borehole Modes: two guided, two leaky

Stoneley Wave

Pseudo-Rayleigh Wave

Refracted Compression Wave

Refracted Shear



Sonic Open-Hole Wireline Tools
Micro-Seismogram for Monopole Source

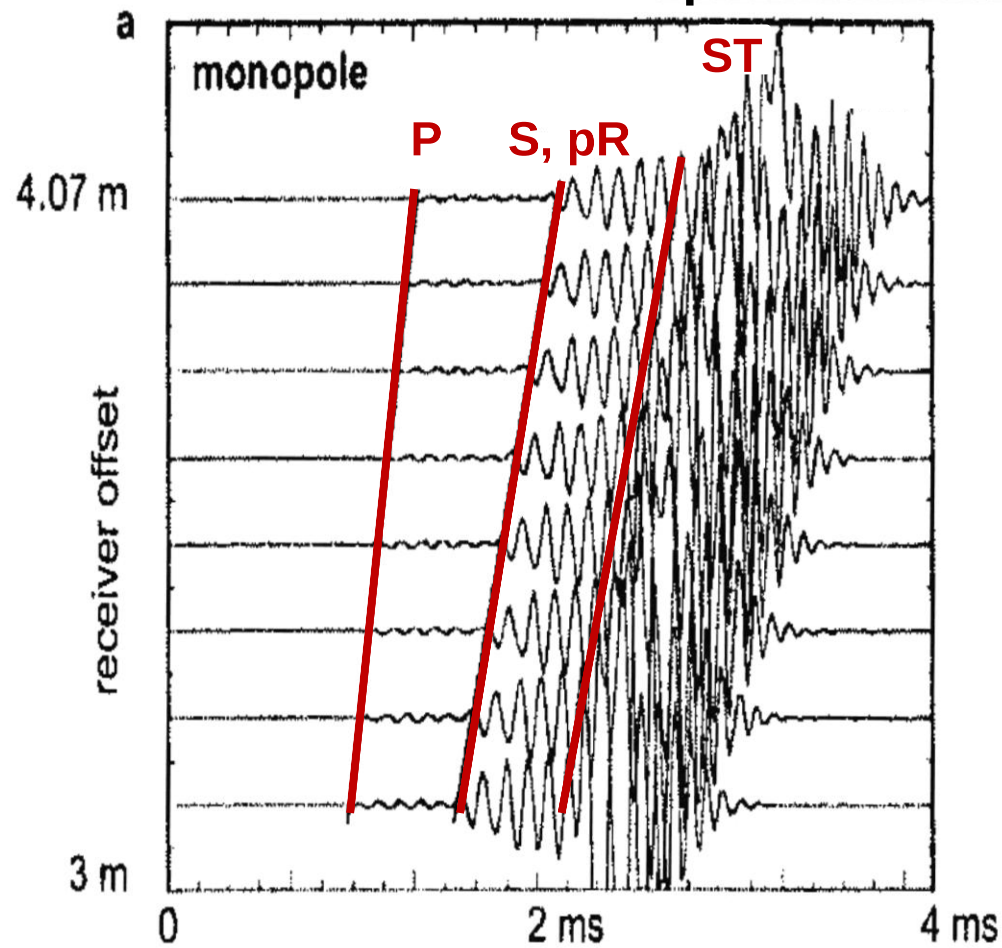
Stoneley Wave (ST)

Pseudo-Rayleigh Wave (pR)

Refracted Compressional (P)

Refracted Shear (S)

Receiver Output



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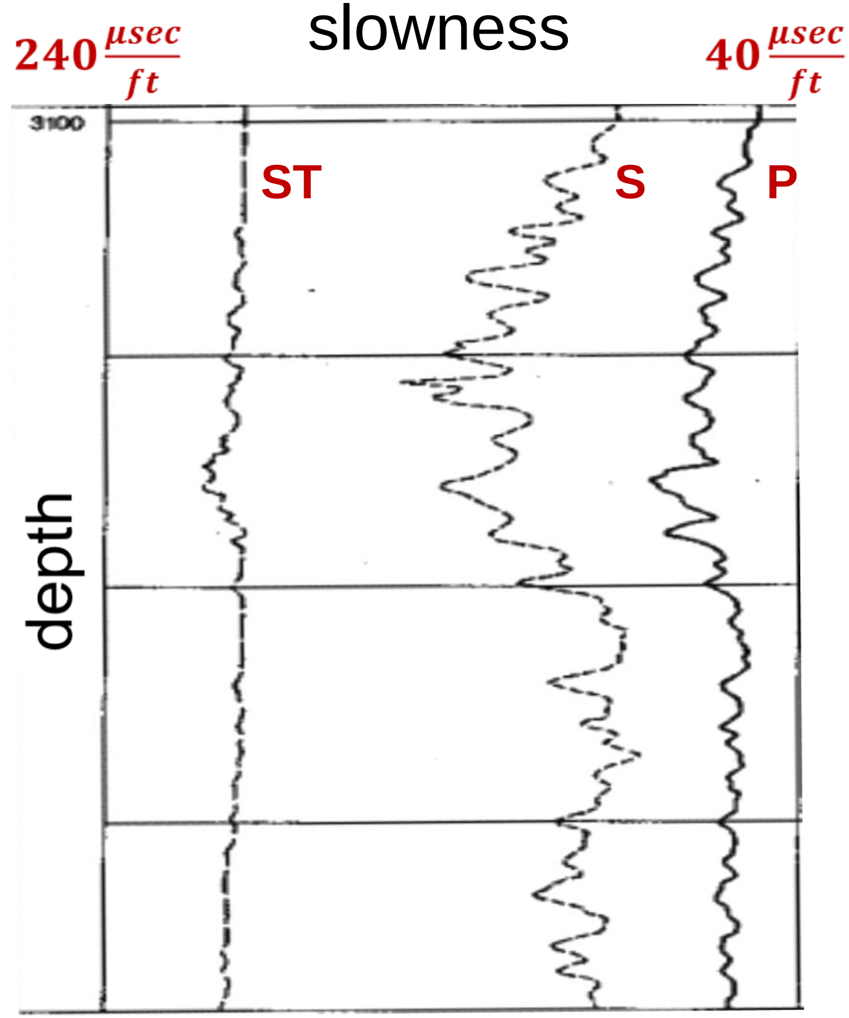
Sonic Open-Hole Wireline Tools

Depth-Based Logs for v_L, v_S, and v_{ST}

Acoustic Log Value

- Lithology identification
- Formation elastic parameters

  K, Y, μ, and ν
- Casing thickness selection
- Seismic tie-in
- Formation porosity
- Formation permeability (v_{ST})



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Sonic Open-Hole Wireline Tools

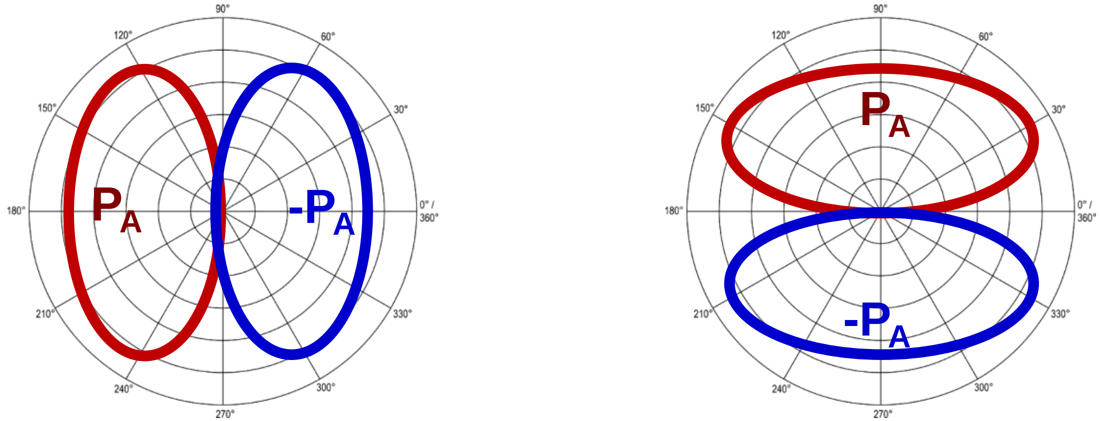
The Big Issue

Assumption: $v_S > v_f$ – “Fast Formation”

Problem: formation can have v_S that is slower than v_f – “Slow Formation”

- no critical angle
- no leaky shear wave
- no v_S measurement

Solution: 2 orthogonal dipole sources added near monopole source



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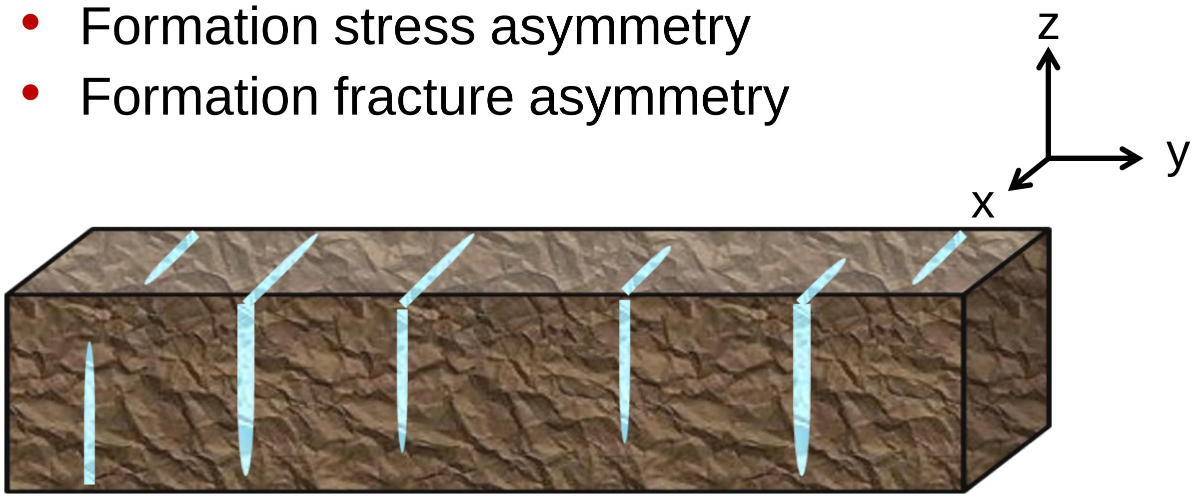
Using the Pseudo-Rayleigh Wave

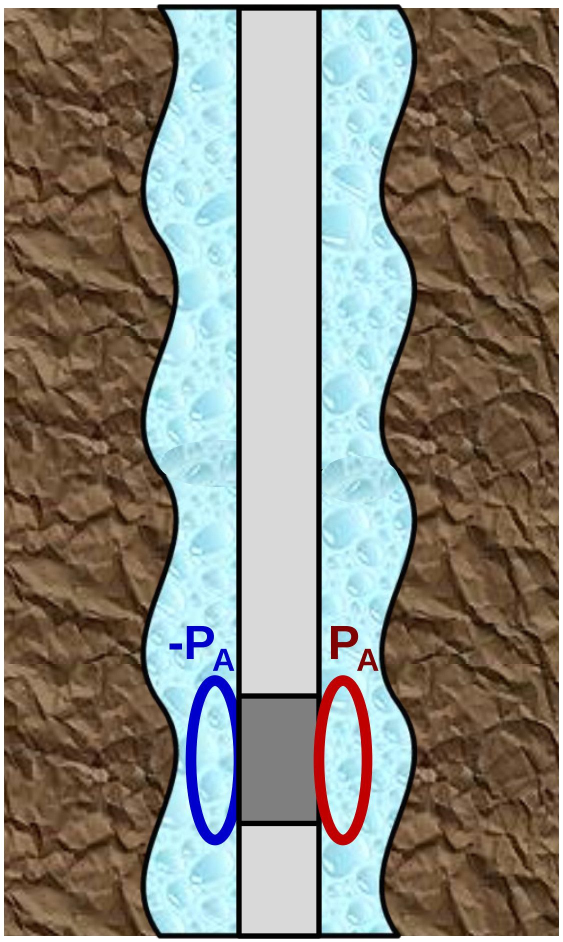
Create pseudo-Rayleigh ”Flexural Wave”

- no low frequency cut off
- low frequency (>1 KHz) $v_{Flexural} \approx v_S$

Two orthogonal 700 Hz dipole sources produce depth-based v_S log

- Formation v_S asymmetry
- Formation stress asymmetry
- Formation fracture asymmetry





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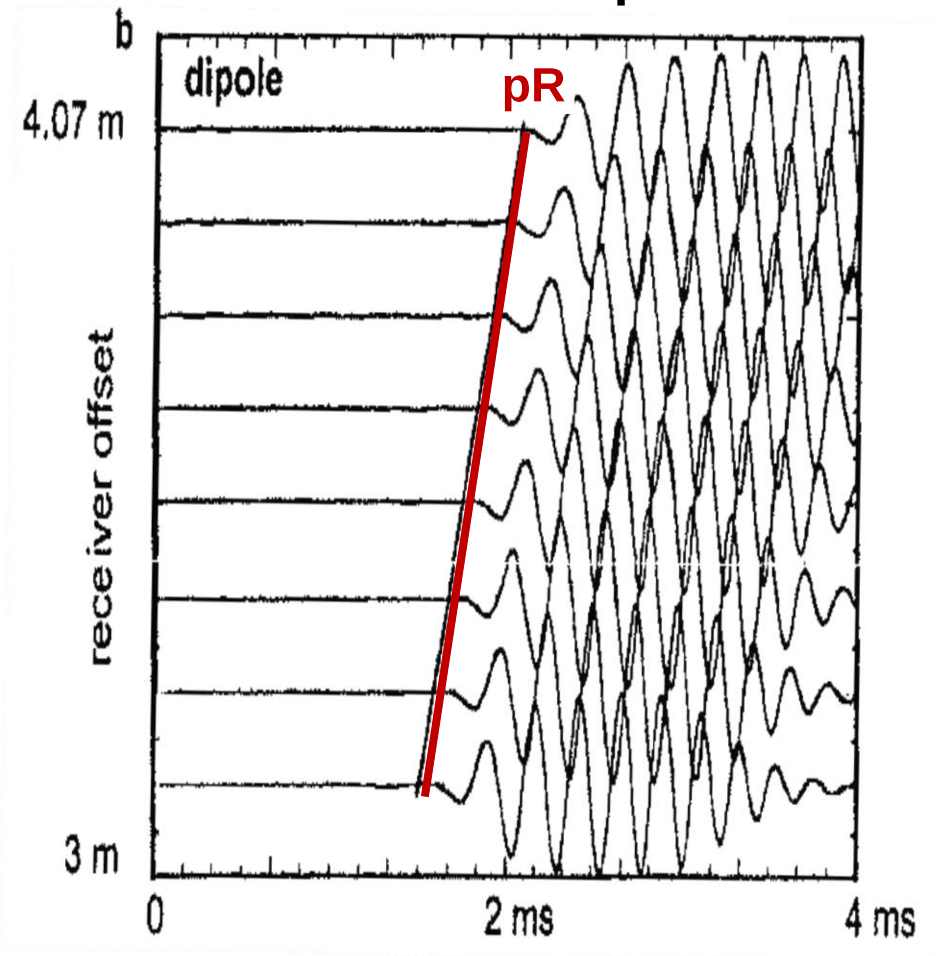
Sonic Open-Hole Wireline Tools

Micro-Seismogram for Dipole Source

Low Frequency

Pseudo-Rayleigh Wave (p-R)

Receiver Output



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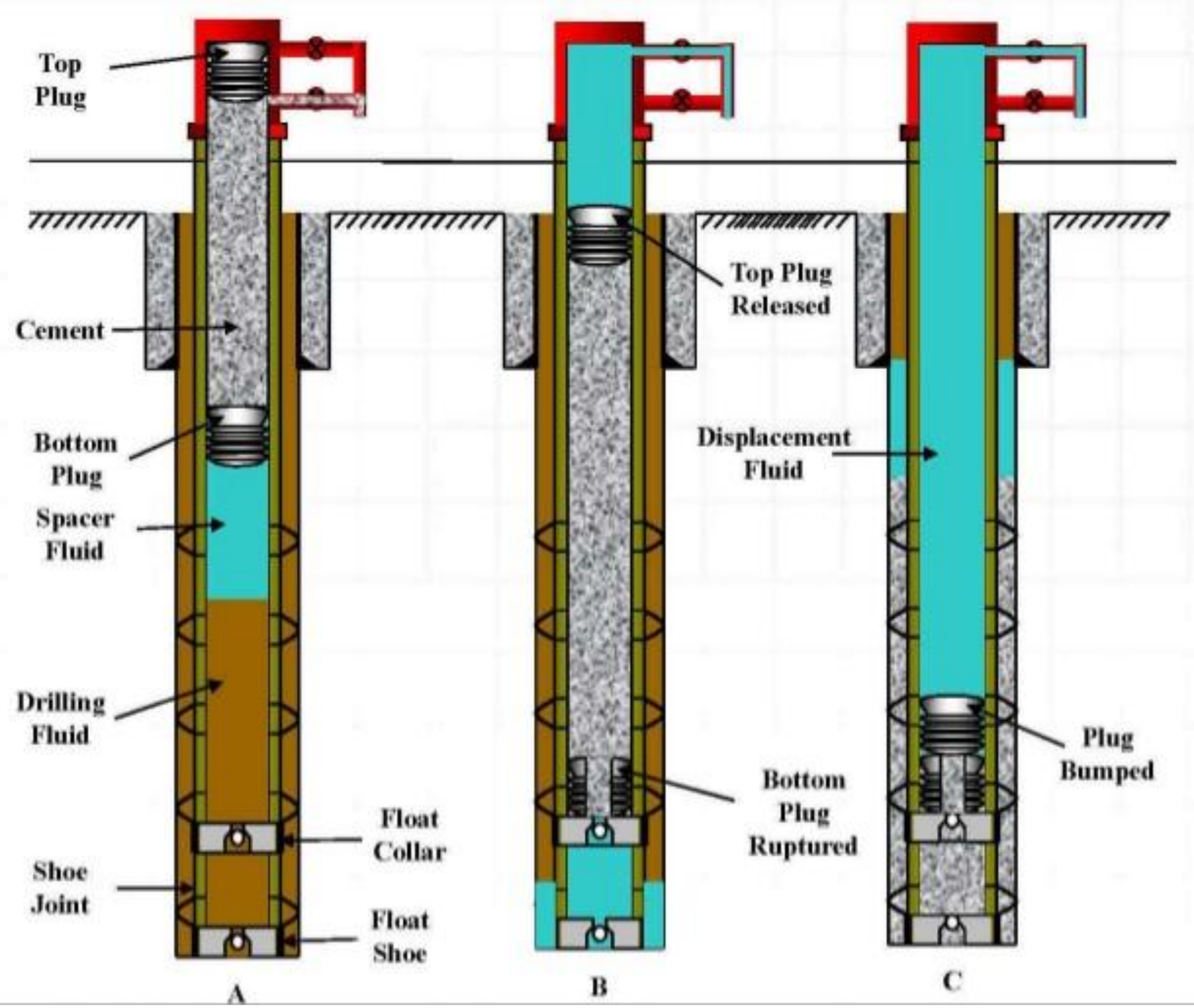
Well Completion Method

Equipment and Process

Oil and Gas Wells

Casing Installation and Cementing Process

- Float collar and shoe installed at well bottom
- Threaded casing and centralizers installed to well bottom
- Spacer fluid, bottom plug, cement, top plug added
- Pressure increased, top plug displaces to well bottom
- Cement allowed to cure, high pressure removed



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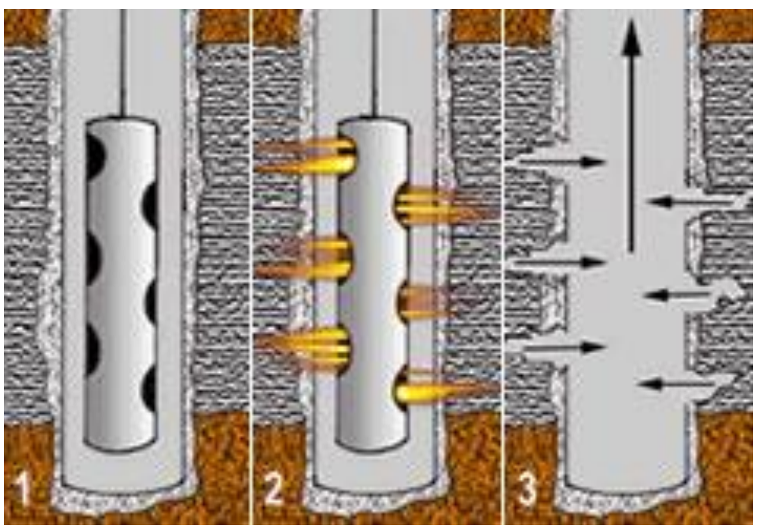
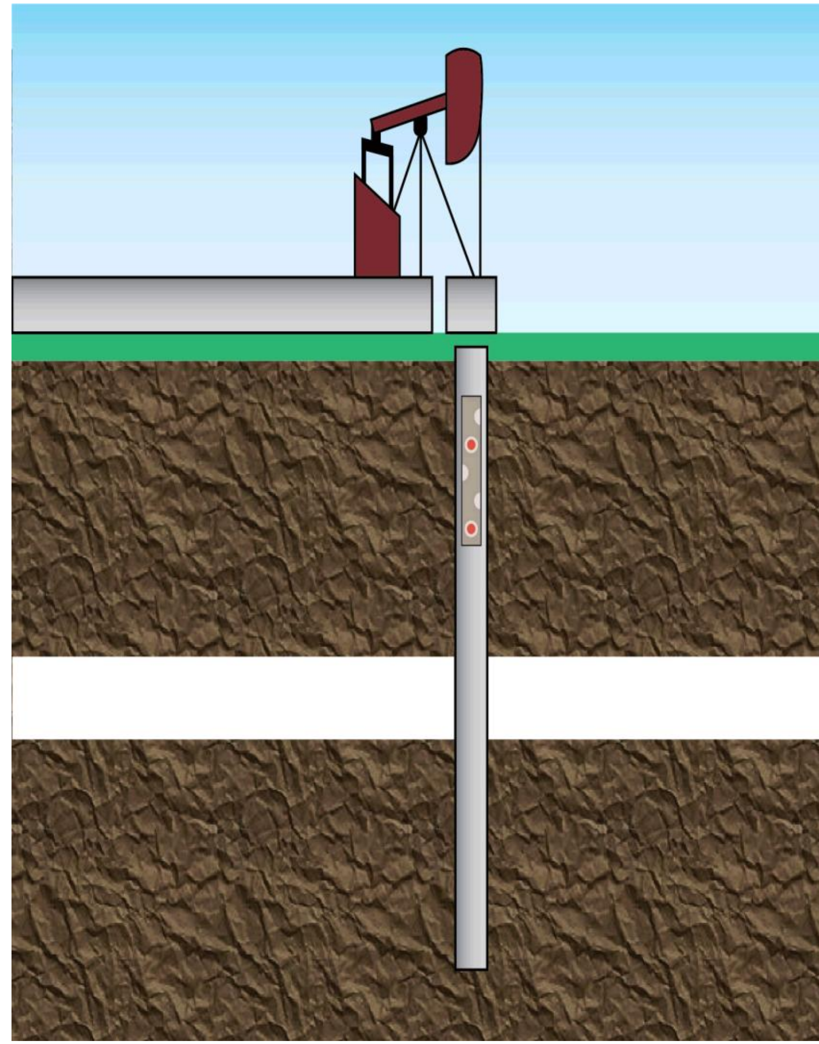
Oil and Gas Wells

Perforation and Pumping Process

- Perforation tool lowered to proper depth (pay-zone behind production casing)
- Explosives remotely fired, holes in casing created
- Pumping and recovery can begin





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Ultrasonic Cased Hole Logging

Casing Thickness Inspection (CTI) and Cement Bond Evaluation (CBE) Using Ultrasound

Ultrasonic Cased Hole Wireline Tools

Measuring the Steel Casing and Cement Condition

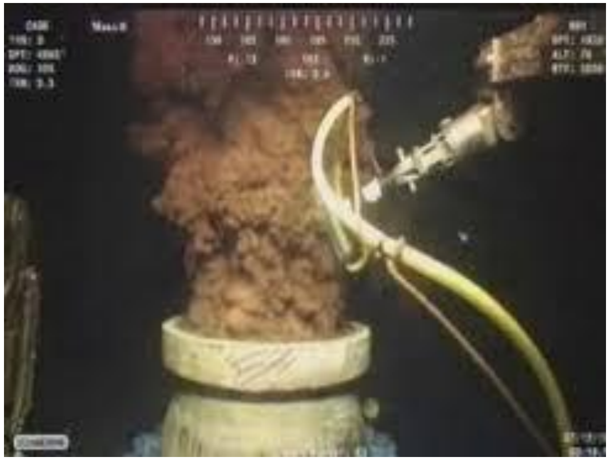
“Cased-hole” wireline logging is also performed as needed. This is not for formation evaluation, rather it is for well structural health inspection.

Potential Problems

- Casing metal loss to galling or corrosion
- Missing or poorly bonded cement sheath

Ramifications

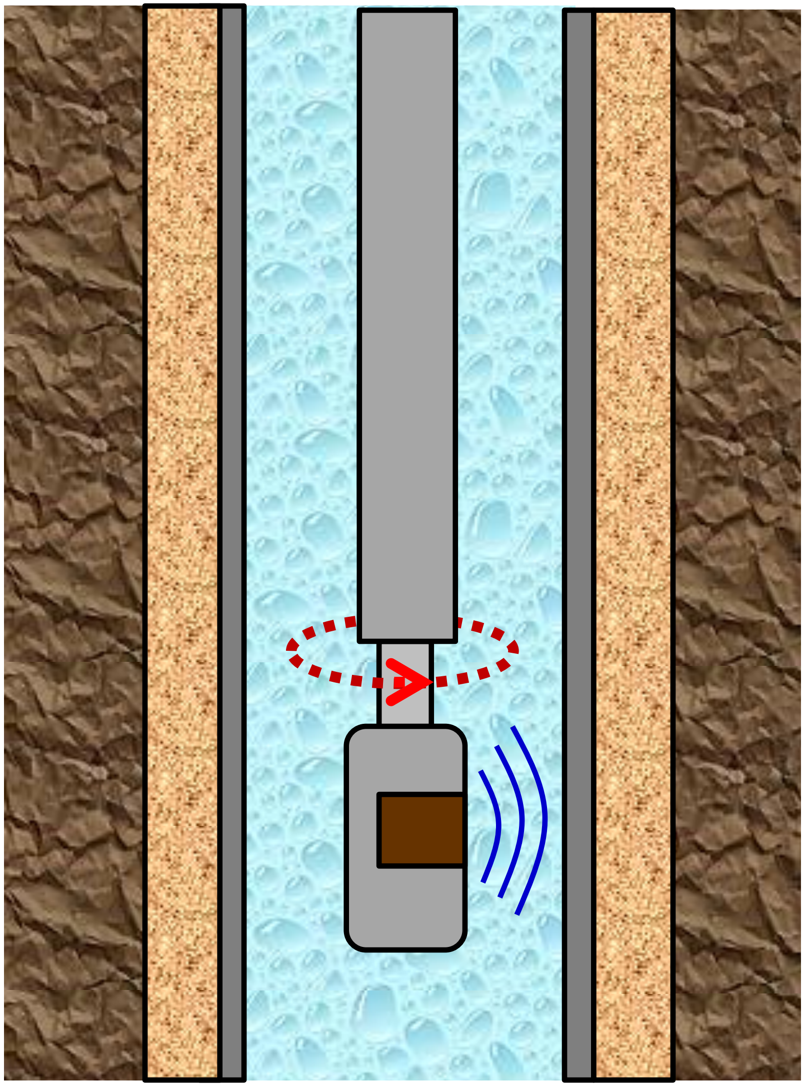
- Blowout prevention
- Zonal fluid contamination



Ultrasonic Cased Hole Logging Tool

Casing Thickness, Cement Bond Log

Tool with ultrasonic transducer on a rotating head in fully cased and cemented well



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Ultrasonic Cased Hole Logging Measurement

Thickness Resonance Condition

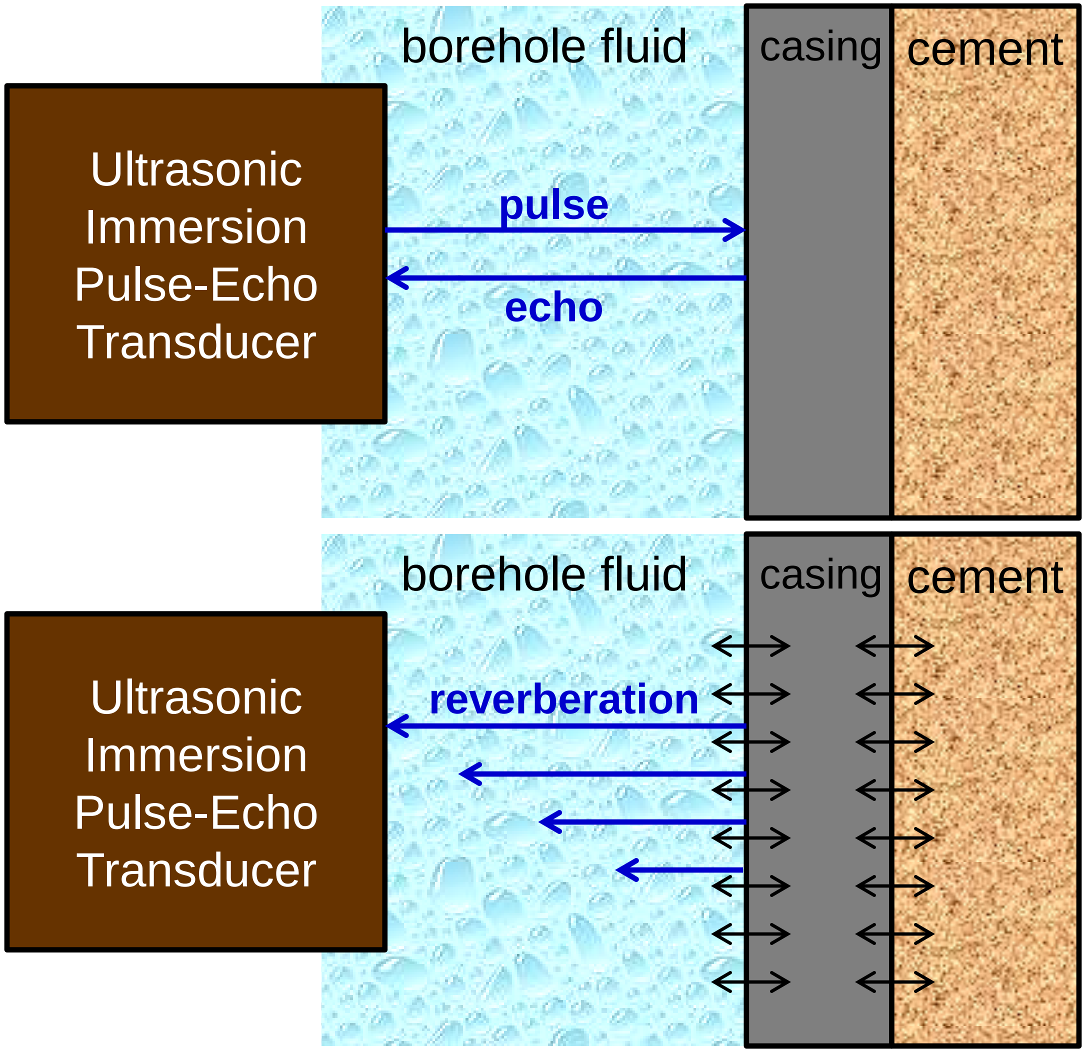
Steel Casing Thickness t

6mm to 12mm nominal

19mm to 25mm for HP wells

Steel Casing Thickness Mechanical Resonance,

$f_t = \frac{v_C}{2t}, v_C \approx 5800\, m/s$



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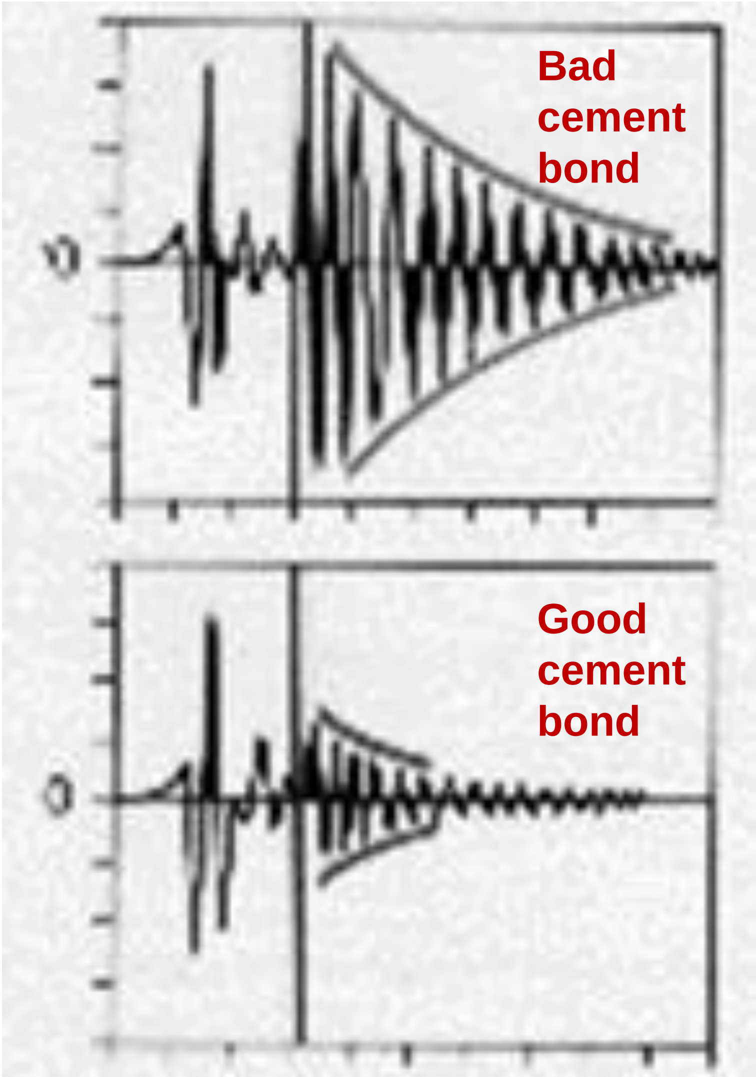
Ultrasonic Cased Hole Logging Measurement

Reverberation Analysis

Measurement – Reverberation Analysis (10X for clarity)

- Fourier analysis of reverberation determines local casing thickness, identifies localized metal loss
- Rate of reverberation decay determines cement bond quality and cement impedance (2 to 12 MRayl)



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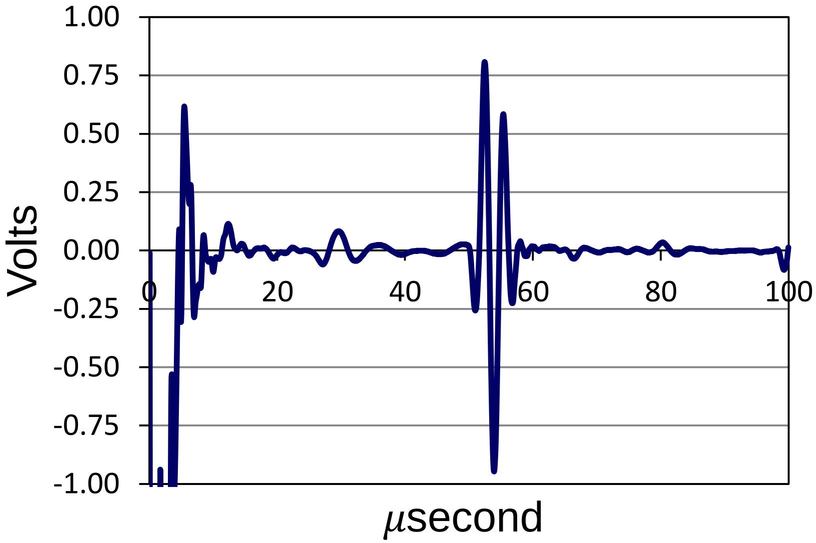
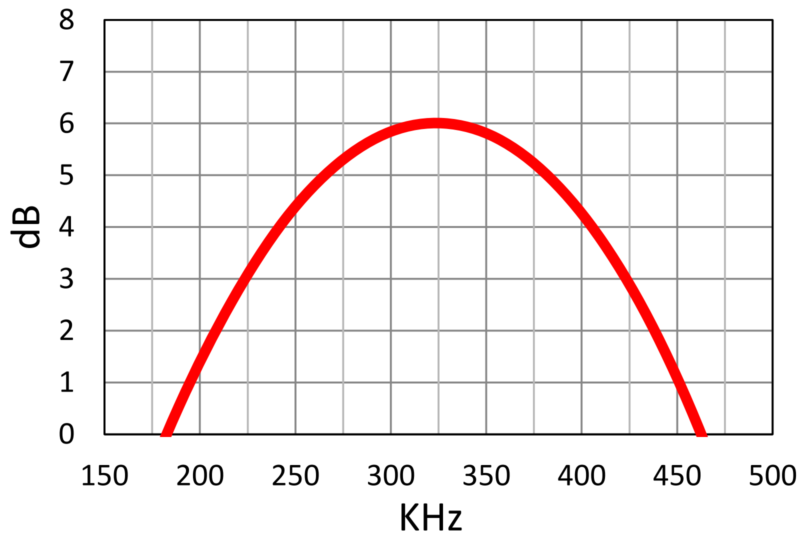
Ultrasonic Cased Hole Logging Transducer

High-Bandwidth, Short-Ringdown

Transducer

- Pulse band should contain resonance frequency and expected frequencies after metal loss
  - Transducer shown emits 183 KHz to 470 KHz, designed for evaluating 0.5” nominal casing eroding to 0.2”





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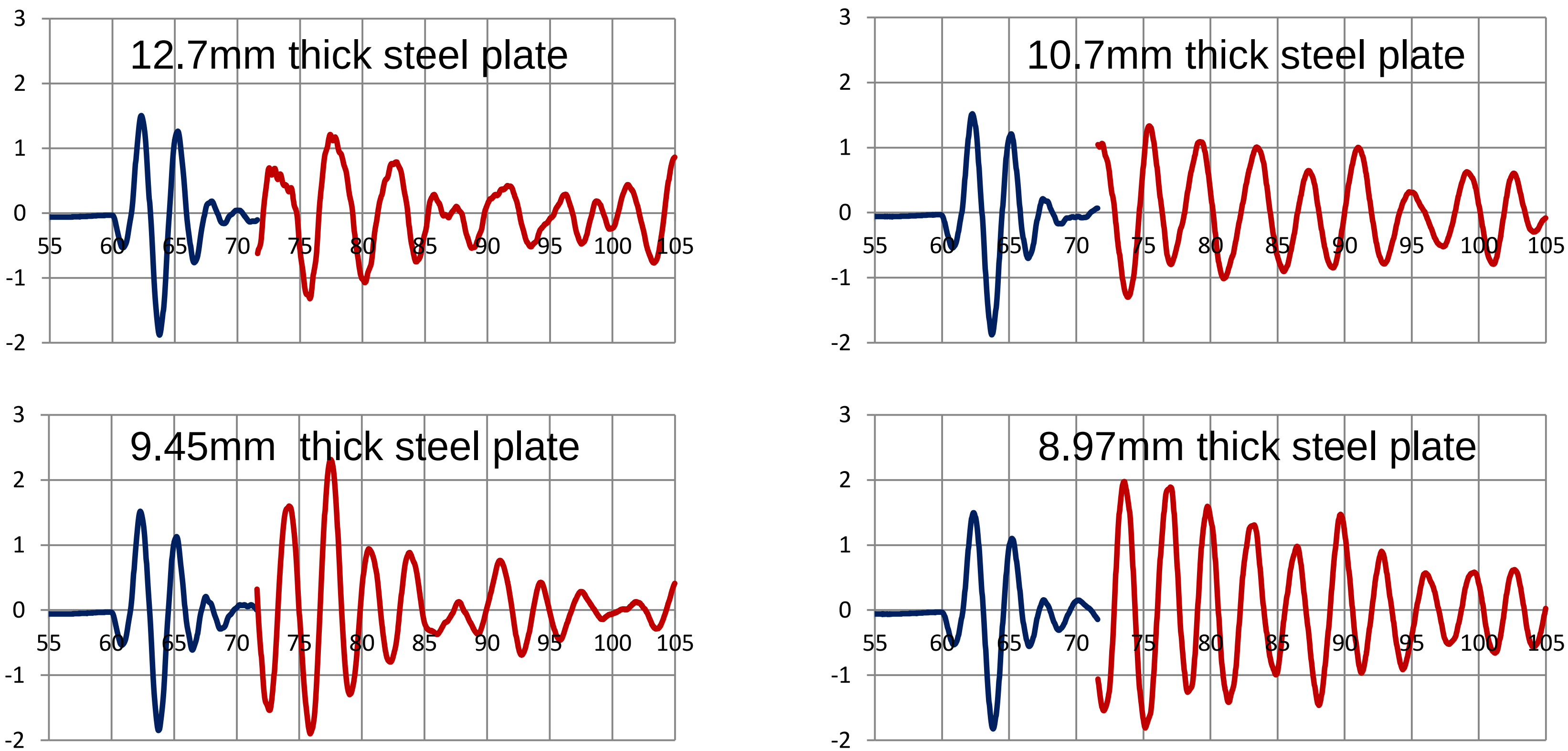
Ultrasonic Cased Hole Logging Transducer

Frequency Content of Reverberation

Pulse-echo data from steel plates:

12.7mm, 10.7mm, 9.45mm, and 8.97mm thick



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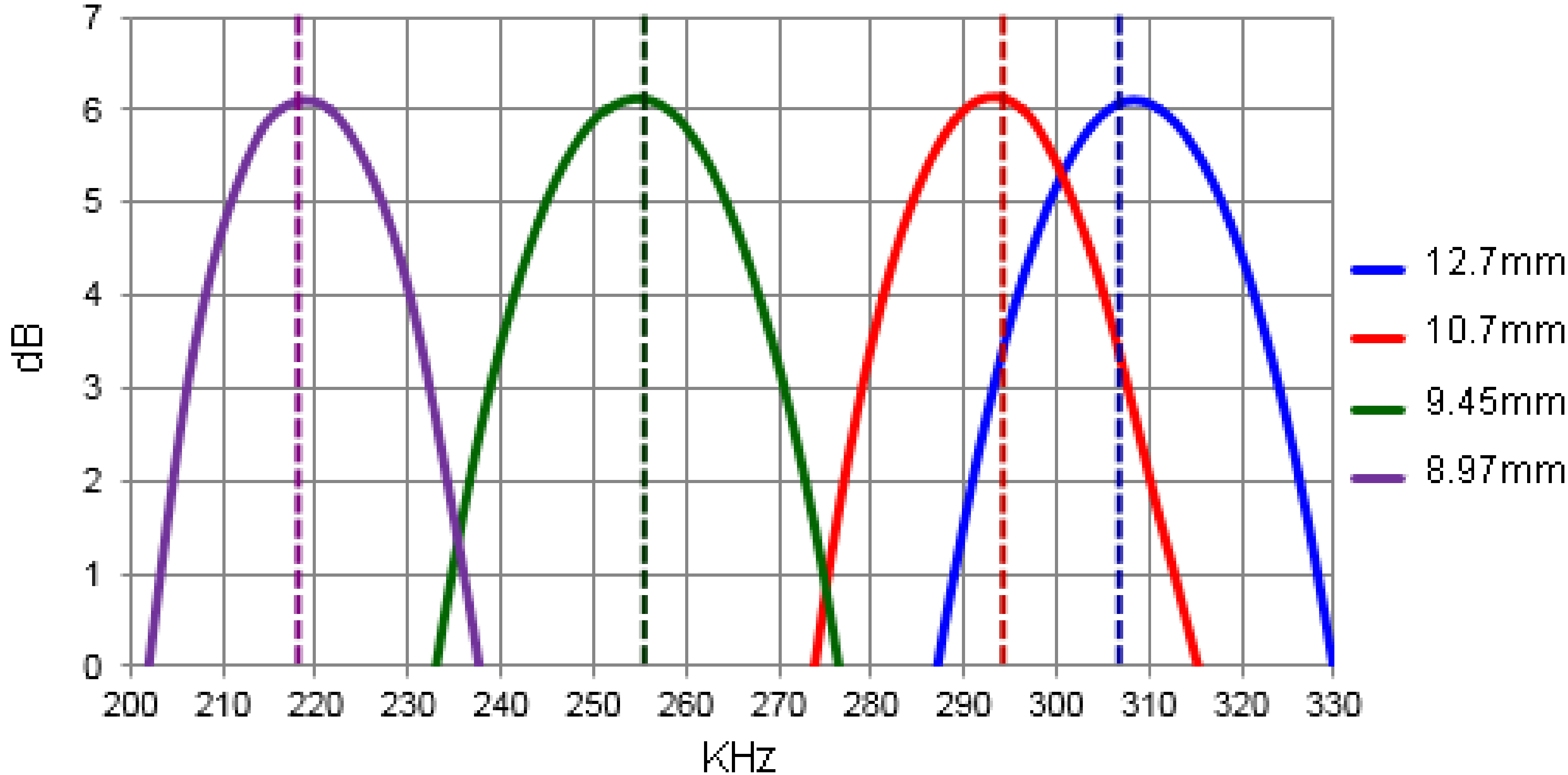
Ultrasonic Cased Hole Logging Transducer

Frequency Content of Reverberation

Fourier spectrum show excellent correlation between measured and predicted (dashed) resonant frequencies



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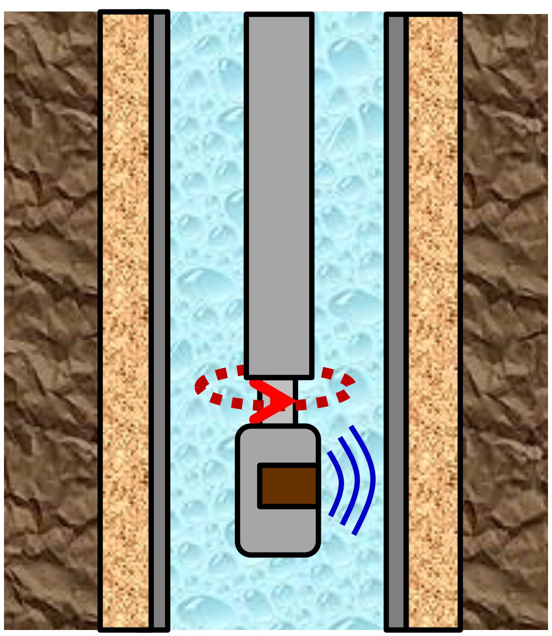
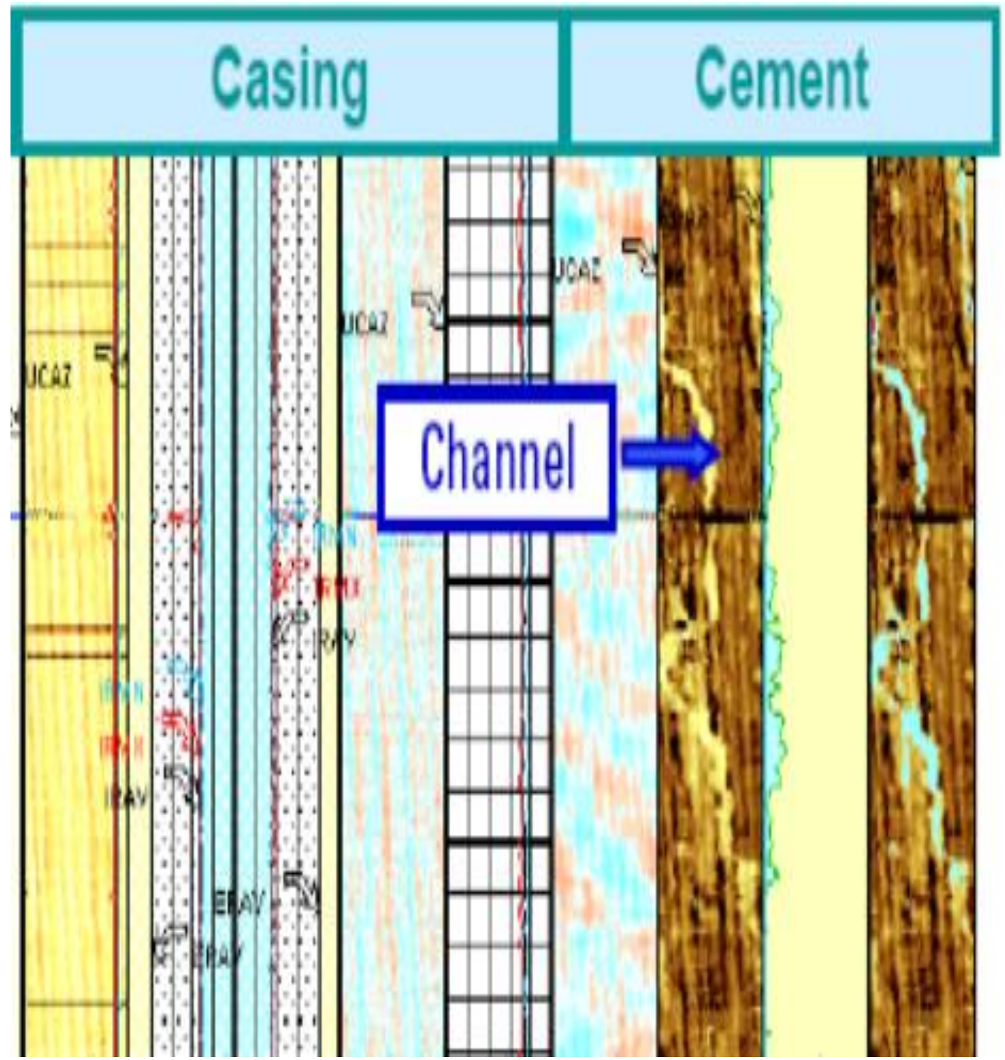
Ultrasonic Cased Hole Logging Tool

Casing Thickness, Cement Bond Log

- Motorized rotating head yield azimuthal coverage
- Tool retrieval yields vertical coverage





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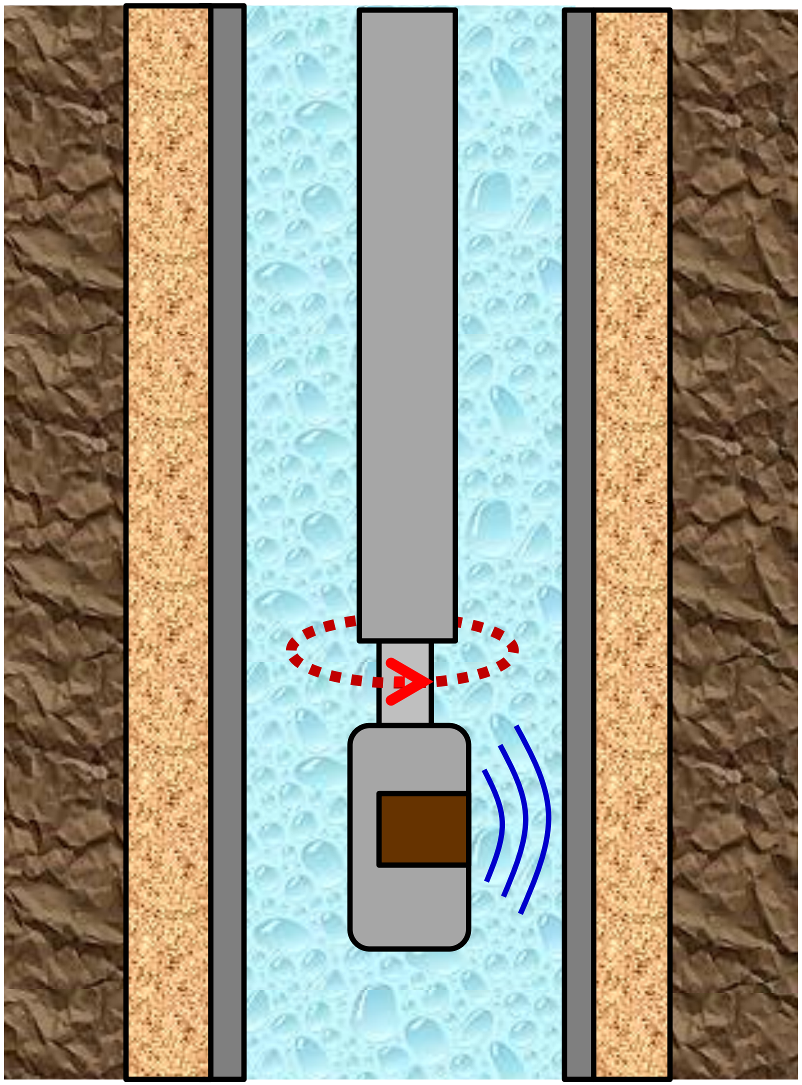
Ultrasonic Cased Hole Logging Tool

Major Weaknesses

Environments of non-functionality

- High attenuation fluid – Unusable in heavy drilling mud or gas-filled fluid
- Thick casing (>0.75”) – pulse-echo transducer response becomes insufficient below 150 KHz
- Lightweight cement (<3.0 MRayls) – decay indiscernible from decay of free pipe



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Thank you!