CHAPTER 7:
ROCK ACOUSTICAL AND RELATED MECHANICAL BEHAVIOUR

7.1 GENERAL INTRODUCTION

The velocity of a pulse through a solid or fluid medium is understood to be an important method to understand the composition of rocks. The behaviour of the pulse is, among other things, depending on the mechanical behaviour of rocks. The propagation of acoustic waves through rock and in the borehole results into the following rock mechanics related physical properties that are measured for characterisation:

- the shear wave velocity,
- the shear wave attenuation,
- the compressional wave velocity,
- the compressional wave attenuation, and,
- the amplitudes of the reflected waves.

The sonic or acoustic log was developed in the 1950's to provide a detailed record of acoustic velocities along the well trajectory. If interval travel times and the depth intervals corresponding to the travel times are recorded a velocity depth profile can be constructed. This profile can be used to convert seismic events, recorded in two-way travel times, to images that can be plotted as function of depth. Soon it became apparent that the sonic travel times can also be used for other purposes such as:

- porosity estimation,
- lithology assessment together with density & neutron tools,
- gas detection, and most important of all,
- to evaluate together with the density tool mechanical properties of the rock.
- cement-bond property-measurements and fractured-zone identification, which are based on measurements of wave attenuation. Also, the assessment of reflected-wave amplitudes is applied to locate vugs and fractures, in order to evaluate fracture orientations and to inspect casings.

Hence, acoustic logging in open holes (uncased boreholes) consists mainly of acoustical velocity measurement. This measurement, usually called a sonic log, is a record of the time, Δt, which is required for an acoustic wave, in order to travel a given distance through the formation that surrounds a borehole. This parameter is named the acoustic transit time, which is generally defined in microseconds per foot. Velocity, v, and transit time, Δt, are related by:

$$\Delta t = \frac{10^6}{v} \quad , \qquad \text{(eq. 7.1)}$$

where; Δt *is* in μsec/ft and v is in ft/sec.

7.2 BASIC CONCEPT

The fundamental idea is based on the combined use of a transmitter and one or more receivers that sent specific wave types and receive converted waves. These waves or pulses have been sent to a body with a known length and a specific density and texture.

At the source the following wave-types are sent in a pulse:

- *compressional or longitudinal waves*:
  They can be considered as a series of zones of compression and dilatation that move in the direction of the propagation. These compressional waves move through both solids and fluids.
- *shear wave or transverse waves:*
  They consist of a series of vibrations motions perpendicular to the direction of movement. They are moving through solid media. In rigid matter the motion of the particles perpendicular to the wave propagation be accommodated. For that reason, the shear wave only is present in solids, because of its shear strength.

So, acoustic velocity of rock depends on the elastic properties. In the coming sections we discuss the relation between rock strength and pulses through a rock *in "the basic concepts of elasticity and elastic wave propagation in (porous) media"*. And so the parameters that influence acoustic velocity and related equations are also explained.

7.2.1 RIGIDITY OF ROCK

Rigidity, or stress and strain, or elasticity of rock, concerns to the connection between the external forces on a body and the resulting change in size and shape. Force is described by force per unit area, or stress.

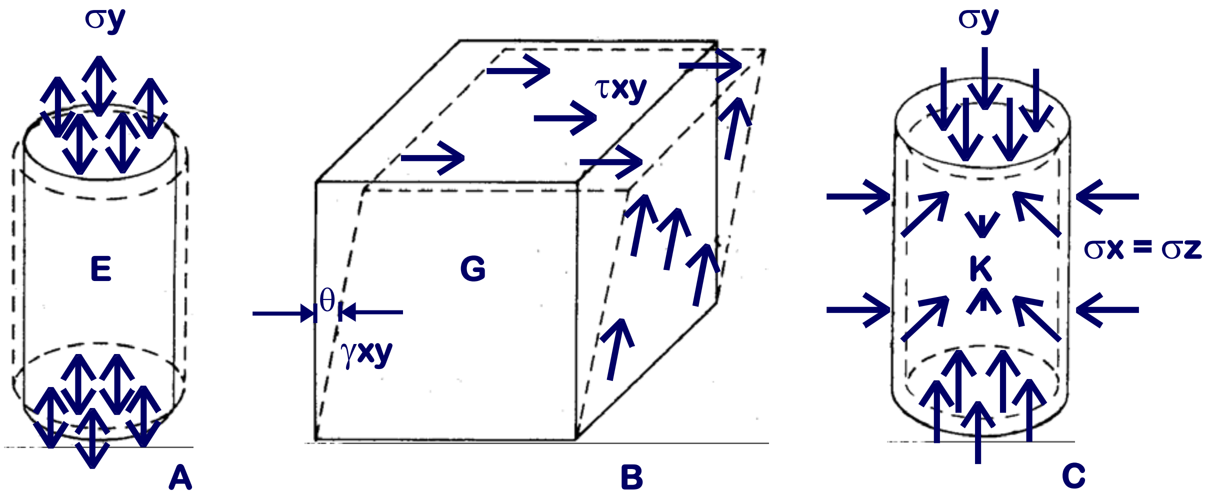

Figure 7. 1: Loading geometries to define elastic moduli. A: Young's modulus or Poisson's ratio, B: Shear modulus, C: Bulk modulus.

7.2.1.1 STRESS-STRAIN RELATIONS

- A force applied perpendicularly to a cylinder of length L and diameter d and away from or to the body on which it acts results in respectively a tensile stress or a compressive stress that causes a change of ΔL (figure 7.1a).
- With a tangential force applied, then it is referred to as a shear stress (fig.7.1b). Note that a shear stress causes deformation by displacement with no volume change.
- Stress induced deformation and displacements are strains.
- Strains derived by compressive and tensile stresses are named longitudinal strains, ε_l, and transverse strains, ε_t .

$$\varepsilon_l = \frac{\Delta L}{L}, and\cdot, \varepsilon_t = \frac{\Delta D}{d} \qquad \text{(eq. 7.2, eq. 7.3)}$$

with; L and d as the respective length and diameter of the cylinder and ΔL, Δd the respective displacements. The shear stress result is named the shear strain, ε_s, (figure 7.1b), which is defined by:

$$\varepsilon_s = \frac{\Delta L}{L} = tan\theta \qquad \text{(eq. 7.4)}$$

Here θ is the deformation angle, and $\varepsilon_s \approx \theta$, when the strain is small.

The elastic constants are the elastic properties of a matter and defined for strains within the elastic limit[1], as follows:

Young's modulus (*E*); (Figure 7.1a)
the Young's modulus is the ratio of tensile or compressive stress to the corresponding strain:

$$E = \frac{F \cdot L}{A \cdot \Delta L} \qquad \text{(eq. 7.5)}$$

With an *E* for most rocks, ranging from 10^{10} to 10^{11} Pa. The Young's modulus is closely related to the Poisson's ratio.

Poisson's ratio, (μ); (Figure 7.1a)
The Poisson's ratio is the explication of the geometric change of shape under stress and it is defined as the ratio of transverse to longitudinal strains:

$$\mu = \frac{\varepsilon_t}{\varepsilon_l}, \qquad \text{(eq. 7.6)}$$

where, in the case of a cylinder, μ is expressed as:

$$\mu = \left(\frac{\Delta d}{d}\right) \bigg/ \left(\frac{\Delta L}{L}\right) \qquad \text{(eq. 7.7)}$$

In general, for rocks, the Poisson's ratios are in between 0.05 and 0.40, with an average for sedimentary rocks of about 0.25.

Shear modulus, (*G*); (Figure 7.1b)
The shear modulus describes the ratio of shear stress to shear strain:

$$G = \frac{F}{A \cdot \theta \cdot}, \qquad \text{(eq. 7.8)}$$

with a G of about 0.3 to 1.5 times E, for a major part of the rocks.

Bulk modulus, (*K*); (Figure 7.1c)
The bulk modulus is a magnitude of the stress/strain ratio when a body is exposed to uniform compressive stress. The stress or, in this case, pressure, *p*, is related to volume change, ΔV, by:

$$K = \frac{p \cdot V}{\Delta V \cdot}, \qquad \text{(eq. 7.9)}$$

Note that the bulk modulus is the reciprocal of the compressibility.

The previous discussed elastic constants; *E*, μ, *G*, *K*, are dependent of each other parameters, because they can be expressed in the terms of two others. The most frequently applied relationships are:

$$G = \frac{E}{[2(1+\mu)]}, \qquad \text{(eq. 7.10)}$$

and;

$$K = \frac{E}{[3(1-2\mu)]} \qquad \text{(eq. 7.11)}$$

[1] With elasticity the body returns to its original condition if the force causing the strain is removed

7.2.1.2 ELASTIC BODIES AND WAVE PROPAGATION

If an elastic body is imposed by an abrupt stress or pressure, and by that immediately compacted, then in the region with high compaction the particles of the grain frame will distribute, away from the point of impact (figure 7.2). In a wave-like form they are transmitted through the body by a series of compressions and compression releases. This wave propagation is expressed by the following equations:

$$\sigma = A_0 \cos 2\pi\left[f_t - \left(x/\lambda\right)\right], \qquad \text{(eq. 7.12)}$$

and

$$v = \lambda \cdot f \text{ , and , } f=1/t \qquad \text{(eq. 7.13 and 14)}$$

With:

- σ as the stress at any time t, at a distance x within an elastic wave,
- A_o as the amplitude of the stress at the source,
- λ as the wavelength, or the distance between a maximum compression and dilatation (or rarefaction) at any time, τ as the period, or the time interval between successive maximum compressions or dilatations,
- f the frequency of compression and dilatation cycles and v *the* velocity of propagation.

Absorption is weakening of elastic waves, so the wave amplitude, A, at a distance x from the source is:

$$A = A_0 \cdot e^{-\alpha x} \qquad \text{(eq. 7.15)}$$

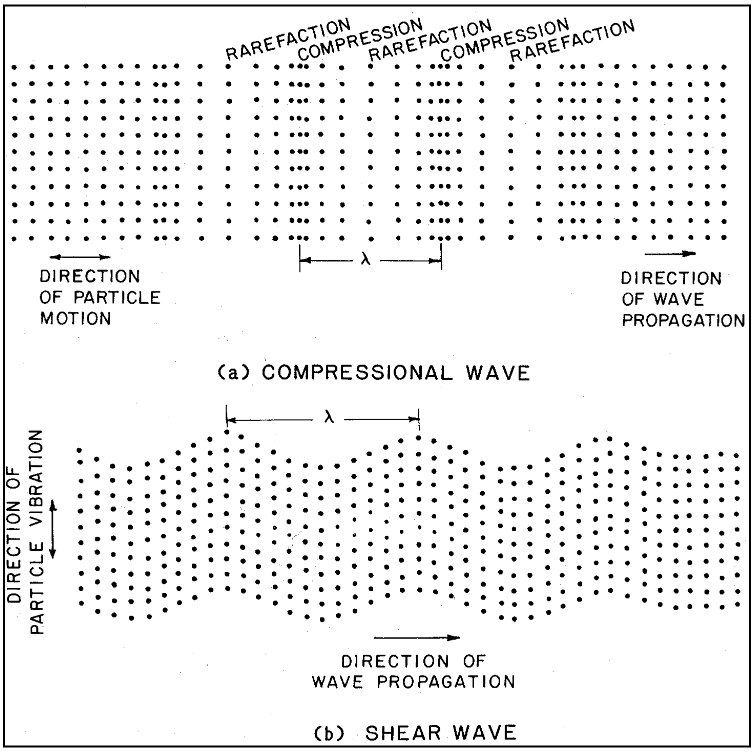

Figure 7. 2: Visualisation of a compressional wave and a shear wave.

Where *a* is the absorption coefficient, which depends on the rock properties through which the wave is propagating. When this weakening or attenuation effects are included in equation 7.12, then:

$$\sigma = A_0 \cdot e^{-\alpha x} \cdot \cos 2\pi\left[f_t - \left(x/\lambda\right)\right], \qquad \text{(eq. 7.16)}$$

Elastic waves can be grouped as body waves and boundary waves. Body waves propagate in unbounded media. Boundary waves arise at the presence of boundaries like a borehole wall (fluid/rock interface). The two main types of body waves are compressional and shear waves.

ACOUSTIC COMPRESSIONAL VELOCITIES AND TRANSIT TIMES IN ROCK MATRICES OF INTEREST IN WELL LOGGING

Material	v_p (ft/sec)	Δt (μsec/ft)
Sandstone	18,000 to 19,500	55.5 to 51.0
Limestone	21,000 to 23,000	47.6 to 43.5
Dolomite	23,000	43.5
Anhydrite	20,000	50
Shale	5,900 to 17,000	170 to 60
Salt	15,000	66.7

Table 7. 1 Examples of acoustic properties

With the <u>compressional- or longitudinal- or P (primary)- waves</u>, the particle movement is in the direction of wave propagation. Here the velocity of compression propagation, v_p, depends on the elastic properties of the rock and can be derived from the equation of motion:

$$v_p = \left[(K + 4/3)G/p\right]^{1/2} = \left\{\frac{(E/\rho)(1-\mu)}{(1-2\mu)(1+\mu)}\right\}^{1/2}, \qquad \text{(eq. 7.17, 7.18)}$$

With ρ as the density of the medium.

In the shear- or transverse- or S (secondary)- waves, the particle motion is perpendicular to the direction of wave propagation and can be derived from the equation of motion as:

$$v_s = (G/\rho)^{1/2} = \left[\frac{E/\rho}{2(1+\mu)}\right]^{1/2} \qquad \text{(eq. 7.19, 7.20)}$$

For shear waves the medium needs to have shear strength, in other words: shear waves only travel through solid material. The compression- and shear wave velocities can be compared with the equations 7.17 to 7.20, in:

$$\frac{v_p}{v_s} = \left[(4/3) + (K/G)\right]^{1/2} = \left\{\frac{2(1-\mu)}{(1-2\mu)}\right\}^{1/2} \qquad \text{(eq. 7.21, 7.22)}$$

Always is in force: $G > 0$ and $K > 0$, so $v_p > v_s$, and because $0 < \mu < 0.4$, as stated before;

$$v_p > \sqrt{2v_s}\ , \qquad \text{(eq. 7.23)}$$

or converted to the transit time, Δt;

$$\Delta t_s > \sqrt{2\Delta t_p}\ , \qquad \text{(eq. 7.24)}$$

with Δt_P and Δt_S as the transit times of the primary and secondary waves. The equations 7.23 and 7.24 show that in under elastic conditions shear waves propagate slower than compressional waves.

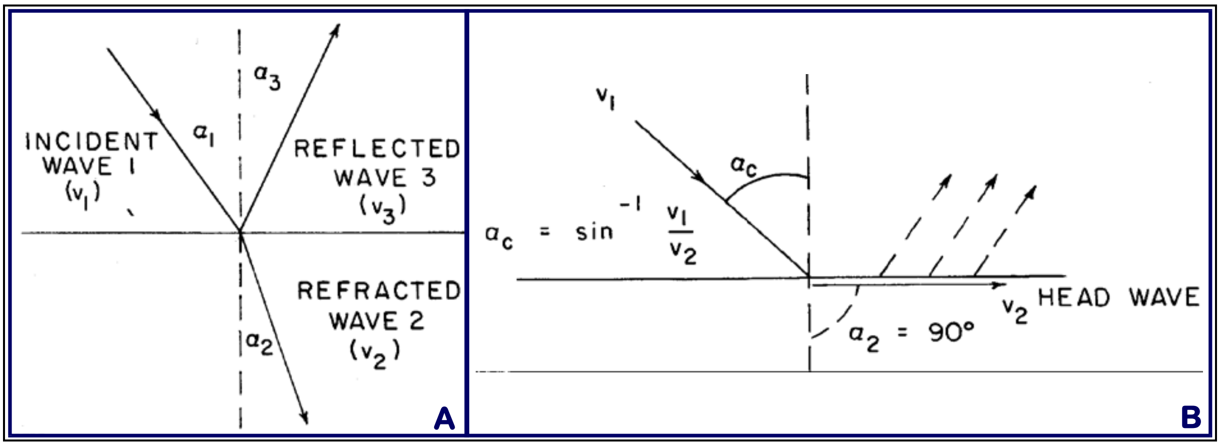

Figure 7. 3.A: Refraction and reflection of elastic waves at the interface of two different substances. B: Head wave created by a wave incident at a critical angle of reaction.

7.2.1.3 THE REFRACTION AND REFLECTION OF ELASTIC WAVES.

Elastic waves encounter phenomena like reflection, diffraction, refraction and interference. Refraction and reflection occur when a wave meets an interface between two substances with different elastic properties. Then a part of the energy of the incident wave is reflected and a part is refracted. The incident wave can be converted into other types of vibrations upon reflection or refraction. This phenomenon is called mode conversion. Figure 7.3a explains the geometry of the rays along which the acoustic waves propagate:

1. A wave with velocity v_1 has an incident at an angle α_1 on a plane boundary separating two media of different elastic characteristics.
2. A wave with velocity v_2 is refracted into the second medium at an angle α_2.
3. A third wave with velocity v_3 is reflected back into the first medium at an angle α_3.

The different velocities $v_{1,2,3}$ are specific for the media and the wave types and when translated to Snell's law:

$$\frac{\sin\alpha_1}{v_1} = \frac{\sin\alpha_{21}}{v_2} = \frac{\sin\alpha_3}{v_3}, \qquad \text{(eq. 7.25)}$$

If the reflected and incident wave are of the same type, then $v_1 = v_3$ and by that $\alpha_1 = \alpha_3$. Further, the angle of refraction α_2 is always different from α_1, since v_1 is different from v_2. In addition the angle α_2 is expressed as:

$$\sin\alpha_2 = \left(\frac{v_1}{v_2}\right)\sin\alpha_1 \qquad \text{(eq. 7.26)}$$

when:

$$\sin\alpha_1 = \left(\frac{v_1}{v_2}\right) = \sin\alpha_C \qquad \text{(eq. 7.27)}$$

As illustrated in figure 7.3b, $\sin\alpha_2 = 1$ and $\alpha_2 = 90°$ and the angle α_C is the critical angle of refraction. This critical refracted wave travels along the interface at a velocity V_2 and is named the **<u>head wave</u>**. It generates energy back into the first medium as it travels along the boundary. <u>Note</u>, that if the incident angle is greater than the critical angle, then no refraction will occur and the wave is totally reflected.

A compressional wave which is travelling in environment 1 or medium 1, at a velocity v_{P1} will generate a compressional head wave in environment 2 if its angle of incidence is critical. This critical angle, "α_{PC} " is defined according to equation 7.27:

$$\sin\alpha_{pc} = \left(\frac{v_{p1}}{v_{2p}}\right) \qquad \text{(eq. 7.28)}$$

A compressional wave that is going through environment 1 or medium 1 will create a shear head wave if its angle of incidence is critical. This critical angle, "α_{SC} ", is also defined according to equation 7.27, as:

$$\sin\alpha_{sc} = \left(\frac{v_{p1}}{v_{s2}}\right) \qquad \text{(eq. 7.29)}$$

When the equations 3.28 and 3.29 are combined, then the result will be:

$$\frac{\sin\alpha_{sc}}{\sin\alpha_{pc}} = \left(\frac{v_{p2}}{v_{s2}}\right) \qquad \text{(eq. 7.30)}$$

<u>As shown in figure 7.4 and already stated, v_{P2} is always greater than v_{S2}, so; $\alpha_{SC} > \alpha_{PC}$</u>

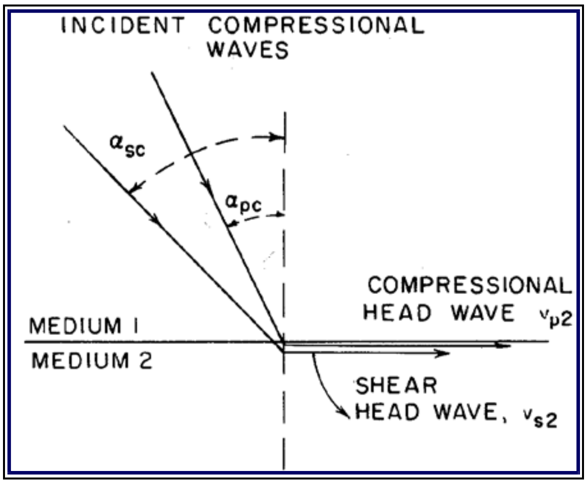

Figure 7. 4: Compressional and shear head waves due to compressional waves at critical refraction angles α_{P2} and α_{SC}.

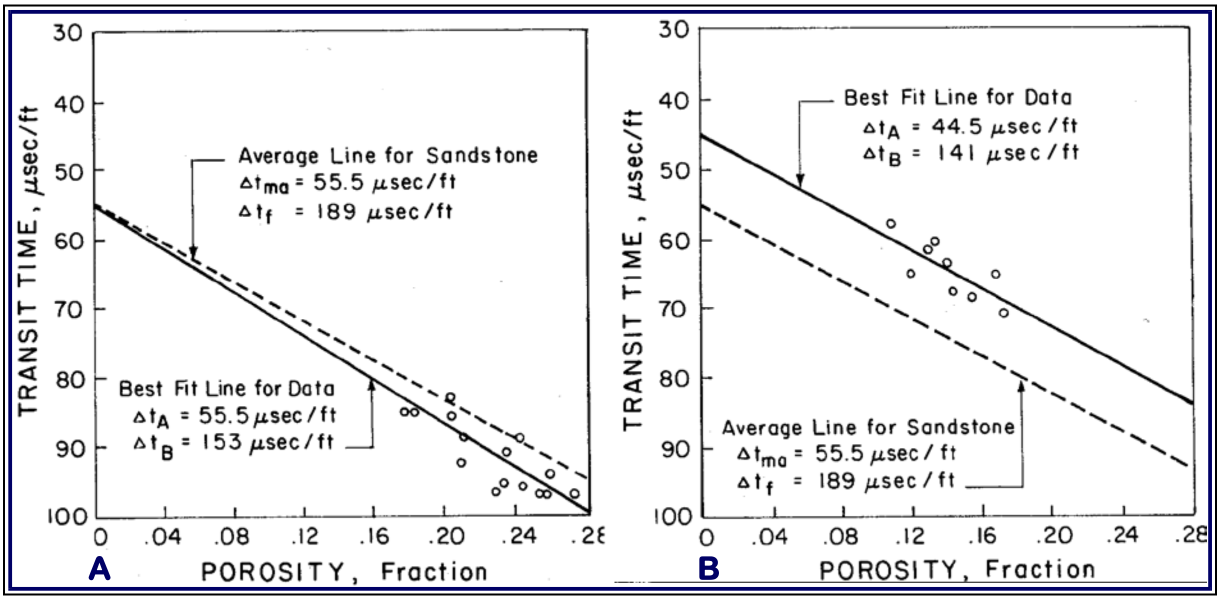

Figure 7. 5: The transit time as a function of porosity for a dense packed sand (B) and a more friable sand (A)

7.2.1.4 ASPECTS OF THE TRANSIT TIME - POROSITY RELATIONSHIP

As shown in figure 7.5a,b, normally there is a good correlation between rock porosity and the acoustic interval travel time. The time-average equation or Wyllie-equation is often used in log analysis. The model of an ideal medium, consists of a layered system of parallel slices alternating a solid and a liquid which is crossed by a wave path perpendicular to the solid/fluid interfaces. Here, the total travel time is equal to the sum of the signal's travel time through the pore-fluid and through the rock-solid fraction.

The equation is simply written as:

summed travel time = travel time in liquid fraction + travel time in matrix fraction, **or:**

$$\frac{1}{v_b} = \frac{\phi}{v_f} = \frac{1-\phi}{v_{ma}} \qquad \text{(eq. 7.31)}$$

or,

$$\Delta t = \Delta t_f \phi + \Delta t_{ma}(1-\phi) \qquad \text{(eq. 7.32),}$$

with,

$v_{b,f,ma}$ as the respective bulk-, fluid- and matrix-velocities, and

$t_{f,ma}$ as the fluid- and matrix- transit times. Now the porosity can be described as a function of transit times, or:

$$\phi = \frac{(\Delta t - \Delta t_{ma})}{(\Delta t_f - \Delta t_{ma})} \qquad \text{(eq. 7.33)}$$

This time-average model shows just a part of the truth. It suggests that only rock matrix and fluid properties influence wave velocity. The effects of the mechanical properties, or previous mentioned moduli, are neglected. However, this perception of

A — ACOUSTIC COMPRESSIONAL VELOCITIES AND TRANSIT TIMES IN ROCK MATRICES OF INTEREST IN WELL LOGGING

Material	v_p (ft/sec)	Δt (μsec/ft)
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Limestone	21,000 to 23,000	47.6 to 43.5
Dolomite	23,000	43.5
Anhydrite	20,000	50
Shale	5,900 to 17,000	170 to 60
Salt	15,000	66.7

B — ACOUSTIC COMPRESSIONAL VELOCITIES AND TRANSIT TIMES FOR FLUIDS OF INTEREST IN WELL LOGGING

Fluid	v_p (ft/sec)	Δt (μsec/ft)
Water		
200 kppm, 15 psia	5,540	180.5
150 kppm, 15 psia	5,375	186.0
100 kppm, 15 psia	5,200	192.3
Pure	4,380	207.0
Drilling mud (26°C)	4,870	205.3
Drilling-mud cake (26°C)	4,980	200.8
Oil	4,200	238.0
Methane (15 psia)	1,600	626.0
Air (15 psia)	1,088	919.0
Ethane (ρ = 0.00125 g/cm^3)	1,010	989.6
Carbon dioxide (ρ = 0.0019776 g/cm^3)	850	1,176.5

Table 7. 2 a,b: Material and fluid velocities and transit times for common media in and around a borehole

porosity vs. travel-times is applicable in friable or loose sandstones and carbonates.

The tables 7.2a,b give an indication of velocities and transit times of various minerals and fluids. Note the correlation between density and velocity.

7.3 THE PRACTICAL METHOD OF APPROACH

As shown in figure 7.6, a magnetostrictive alloy or piezoelectric crystal with a resonance frequency between 5 to 20 kHz is used as material for the transducers. The transmitter sends out pulses with an oscillatory wave-form that generate different wave types :

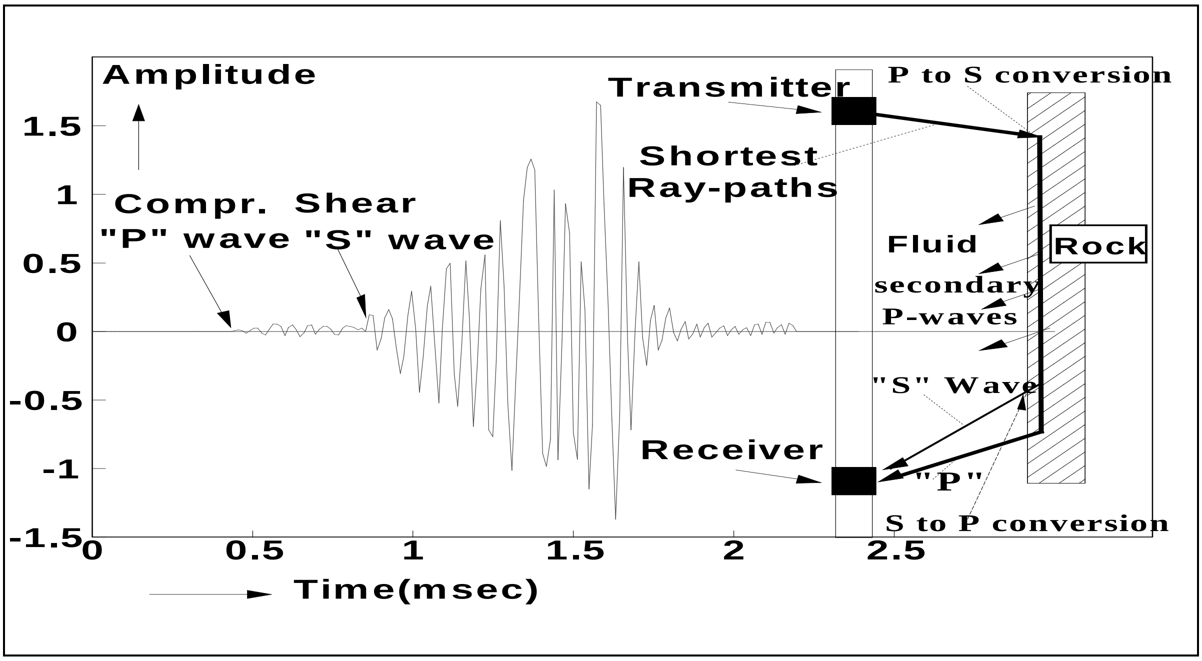

Figure 7. 6: Acoustic pulse recording in a borehole

1. ***The compressional (P) wave***, which is generated by the transmitter in the borehole fluid, will travel in all directions till it hits the borehole wall. At the borehole wall the P-wave will continue in the rock as a fast P-wave, but some of the P-wave energy at the wall will be converted to a shear (S) wave in the rock. Although both waves will expand in all directions from the point of impact only the path along the wall, or the wave of interest, is drawn. The wave travelling along the borehole wall will continuously produce compressional waves back into borehole as indicated by the small arrows. However the velocity of the wave front in the formation will out run the P waves created in the borehole because the P-wave velocity of the formation is higher than velocity of the borehole fluid. The P wave that travels the shortest distance through the mud will be the first one to arrive at the receiver.
2. ***The shear (S) wave,*** that is front travelling along the borehole wall. It will also create secondary P waves in the fluid, because a fluid can only sustain compression waves and has no shear strength. Along the borehole wall a continuous conversion of S back into P waves is the result. The shortest P and S wave paths will not be identical, due to the refraction of the waves on the borehole wall. The slow S wave will according to the law of Snellius refract less to the normal than the fast P wave.

Note: As shown in figure 7.6, the “P” wave, which represents the converted “S” wave, will arrive later than the leading “P” which represents the “P” wave of the formation.

The receiver is triggered by the arrival of the fastest wave (compressional), which is called the "first arrival". About ten pulses are transmitted per second. The measured parameter is the reciprocal velocity, or “travel time, ΔT”, which is expressed in microseconds per foot (equation 7.1). The velocity of the compressional wave depends on the elastic properties of the rock matrix and the fluids in the pore space. The measured travel time is therefore a function of:

- the rock matrix,
- the fluid type, and,
- the porosity.

7.3.1 THE ACOUSTIC TOOL DESCRIPTION

The early tools included only one transmitter and one receiver (figure 7.7a) embedded in a sonde body consisting of rubber (low velocity and high sonic attenuation). The sound pulse travels through the mud (A) at relatively low velocity. The compressional wave is refracted at the formation face and passes through the formation with formation velocity (B). The last lag (C) is again through the mud. The measured travel time is therefore too long due to the passage through the mud. Besides, the physical length of B is not constant since changes in velocity alter the refraction angle. Later versions, as shown in figure 7.7b, incorporated one transmitter and two receivers, a few feet apart, to cancel the above problems. This system measures in effect only the time required to travel interval D, assuming intervals C and E take the same travel times. In that case distance D, which is the distance that the P waves travelled in the formation, is equal to the spacing R1 - R2. The only serious shortcoming of this system is that distance C is not equal to E, when the tool is tilted in the hole or when the hole size changes over short intervals (figure 7.7c). Later versions of the sonic tool like the Borehole Compensated tool (BHC) incorporated two transmitters and four receivers (figure 7.7d). The transmitters are pulsed alternately and ΔT values are obtained from alternate pairs of receivers as indicated. The two ΔT values are averaged to cancel differences in the C and E distances due too tool tilt. The tool consists of a slotted metal body housing, which ensures that the sonic wave travelling through the tool has to follow a labyrinth like path and arrives later than the wave that travels through the formation, and even the direct wave through the mud.

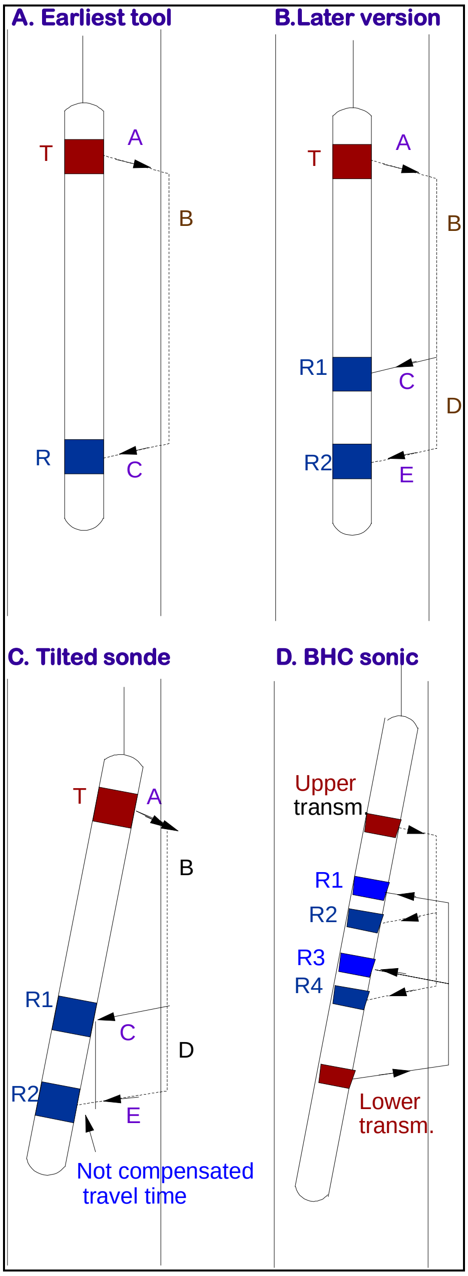

Figure 7.7: A) and B) Older sonic tool versions. C) a tilted sonic tool and D) the borehole compensated tool.

7.3.2 LIMITATIONS OF ACOUSTIC LOGGING

The conventional tools that measure travel times contain a threshold circuit, which triggers when the received signal passes beyond a pre-set threshold. The limitations of the conventional tools are all associated with either this trigger mechanism, the shape of the waveform that is detected or the tool calibration.

- **NOISE**
  Noise can be generated mechanically or by stray electric signals that are picked up by the receiver electronics. If this noise exceeds the trigger level A (figure 7.8) before the arrival of the P wave which travelled through the formation, the receiver circuit will be triggered prematurely and the time measurement will be erroneously small. To limit this possibility all receiver circuits are

switched off for 120 microseconds after transmitter firing. The far receiver is the most sensitive due too longer “open” periods and the larger attenuation of the acoustic wave for longer spacings. Noise spikes are usually intermittent and lead to much smaller travel times over very short intervals. The log readings around these noise induced short travel times can usually be trusted. Editing out noise peaks is very important for seismic applications where a cumulative travel time that is too short will lead too horizons that are located too deep in the seismic section where two way travel times are converted to depth.

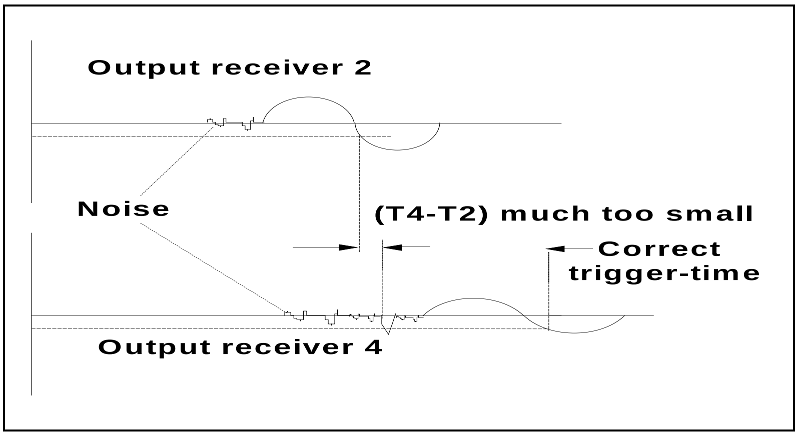

Figure 7. 8: Noise spikes.(Thomas, 1978)

ΔT STRETCH

The second and third cycles of the wave-form are usually of progressively larger amplitude. It was already mentioned above and depicted in figure 7.6, that the signal arriving at the far receiver is usually weaker. As the trigger level is constant for both receivers, triggering at the far receiver can occur too late, causing ΔT to be slightly too large. This phenomenon is shown in figure 7.9, and is called ”ΔT stretch".

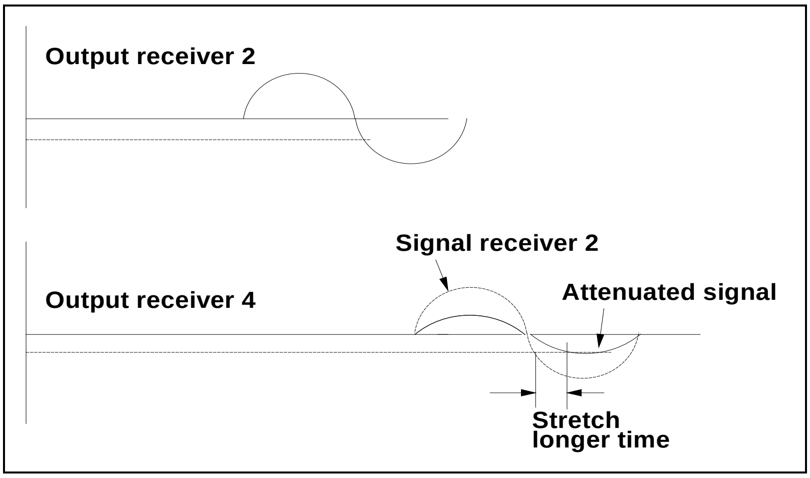

Figure 7. 9: Sonic stretch (Goetz,Dupal)

- **CYCLE SKIPPING**
  Worse than ΔT stretch is the occurrence of triggering at the second or even third cycle (figure 7.10). Cycle skipping leads to a marked sudden shift to a higher ΔT value and later to a similar abrupt shift back to the correct value.

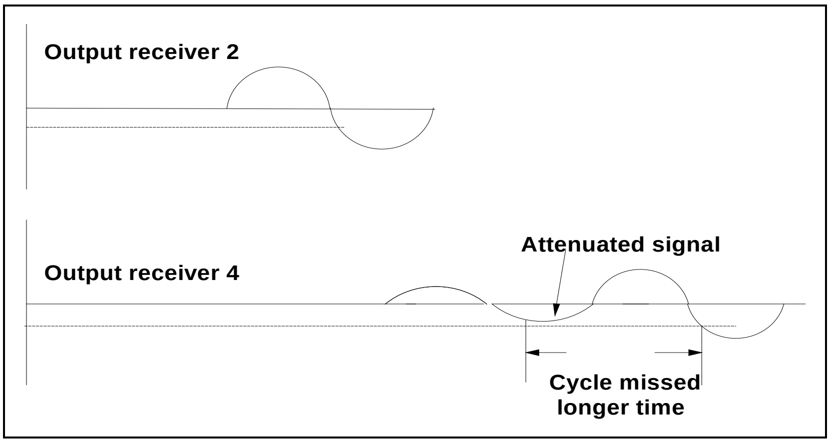

Figure 7.10: Cycle skipping (Goetz, Dupal)

- **CALIBRATION**
  Even when the tool is triggering properly, we require proof that the recorded ΔT is correct. A true calibration shows the response of the complete tool to a standard environment. An excellent check is the recorded transit time in casing which should show the typical value of 57 μs/ft for steel. The transit time of pure anhydrite, which is a common deposit in carbonate areas, is also a good benchmark and should read 48 μs/ft. As with all logs a repeat

section of at least 200 ft should be recorded, which should overlay within a few μ sec with the main log run over the total objective interval.

- **PHYSICAL LIMITATIONS**

A graph of transmitter-receiver (TR) distance against the time to travel from T to R (figure 7.11) shows that the fastest sound path is through the mud at spacings less than a critical spacing "X_C". For larger spacings, the wave path that takes the shortest time to travel, is the one that passes through the formation.

The formation velocity v_1 is measured only when the spacing X_1 is larger than X_C. However assuming that the tool is centred in the hole X_C increases with increasing hole diameter D (larger mud-path X_M), or decreasing formation velocity v_1 (slope $1/v_1$ becomes steeper, and X_C will be larger). A spacing TR1 of 3 feet is usually sufficient to avoid these problems.

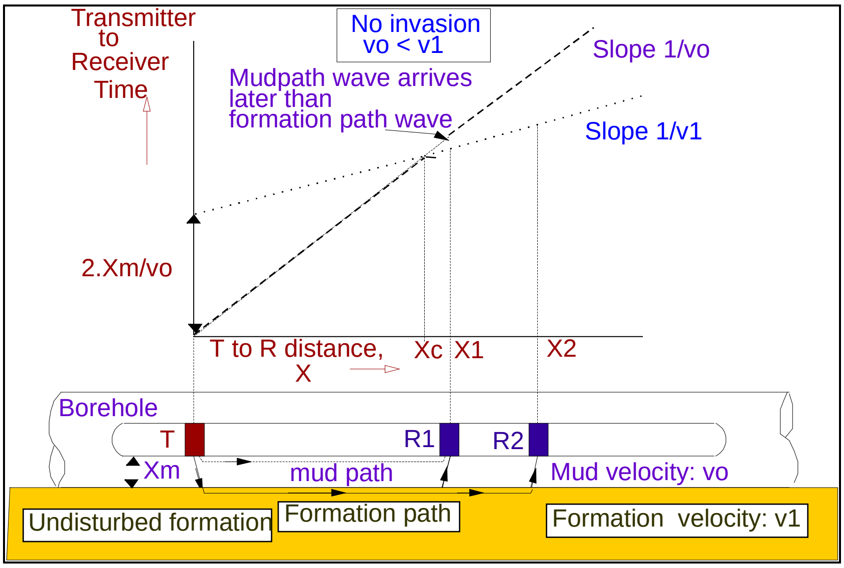

Figure 7. 11: Effect of TR spacing, no altered zone

An "altered" zone around the borehole can exist where the formation has sucked up mud-filtrate. The result will be a lower sonic velocity. Examples are soft hydroscopic clays. This low velocity zone can be circumvented in the same way as the low velocity mud layer by increasing the spacing between transmitter and receiver. However due to the smaller difference between the altered zone velocity and the undisturbed zone velocity the spacing has to increase substantially before the wave, that travels through the high velocity undisturbed zone, out-runs the wave through the low velocity altered zone. The distance X_C even under these adverse conditions is seldom more than 10 feet, hence sonde spacings with this length usually produces accurate readings, whereas the BHC would give too high ΔT readings. When the velocity of the shear wave is lower than the compressional velocity of the mud it is physically impossible for the shear wave to leave the formation. The shear wave should, according to Snellius law for $v_{mud} > v_{forrmation}$, be refracted away from the normal. However, the wave that travels along the borehole has already an angle of 90° with the normal. Hence, no shear wave will produce a secondary compressional wave in the borehole, and detection of the shear wave velocity with this conventional tool is not possible. The critical shear velocity can be calculated with:

$$\frac{\sin(\varphi_{formation})}{\sin(\varphi_{mud})} = \frac{V_{mud}}{V_{formation}} \qquad \text{(eq. 7.34)}$$

in which the $\sin(\varphi_{formation}) = 1$

7.3.3 RECENT TOOLS

Since the mid-eighties new tools became available that were designed to overcome most of the limitations that were discussed in this section.

- **Array Sonic Tool**
  This tool uses two transmitters and up to eight receivers **t**o record the wave trains at 8 source to detector spacings. The 8 wave trains are "stacked" using a process that has some resemblance with cross-correlation. The process is called semblance processing and the maxim in a move-out versus acoustic power plot yield the wave velocities of the Shear and Compressional waves. The effects of cycle skipping, stretch, and noise are removed by the semblance-processing scheme.

- **Digital Sonic Imager**
  It uses not only monopole transmitters and receivers, but also two crossed pairs of dipole transducers that generate and receive preferentially shear waves. This tool can record shear waves even in formations where the shear velocity is less than the mud velocity.

These more advanced tools will be discussed in more detail in the third year's Petrophysical course for Petroleum Engineers and Geophysicists.

7.4 APPLICATIONS OF ACOUSTIC LOGS

The Acoustic logging tools have a wide range of applications:

- Porosity determination in consolidated formations
- Mechanical properties in combination with the density log
- Acoustic impedance determination in combination with the density log
- Velocity depth profiles for seismic calibration
- Lithology indications from the ratio of compressional velocity over shear velocity
- Horizontal and lateral monitoring of drillings for civil engineering purposes, i.e. Tunnel boring and horizontal drilling for gas-/oil-/water-/electrical-/emergency-piping.