Rock Physics

From mm. to Km. scale

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7-Sonic logging

Some slides from P. Glover and S. Gautier.

Contents :

I. **Introduction**

➢ THE SONIC OR ACOUSTIC LOG

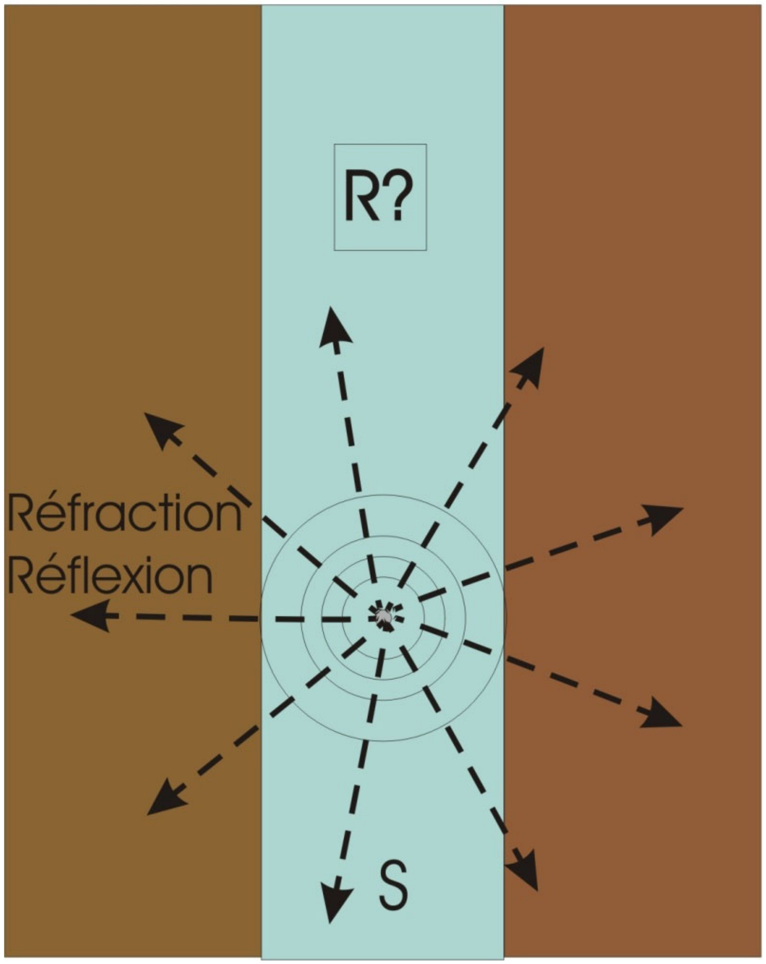
The *sonic* or *acoustic* log measures the travel time of an elastic wave through the formation. This information can also be used to derive the velocity of elastic waves through the formation.

The main uses are:

- calibrate a seismic data set (i.e., tie it in to measured values of seismic
- velocity).
- Provision of "seismic" data for the use in creating synthetic seismograms.
- Determination of porosity
- Stratigraphic correlation.
- Identification of lithologies.
- Facies recognition.
- Fracture identification.
- Identification of compaction.
- Identification of over-pressures.
- Identification of source rocks (oil).

I. **Introduction**

➢ Theory



Pulse

Wave propagation

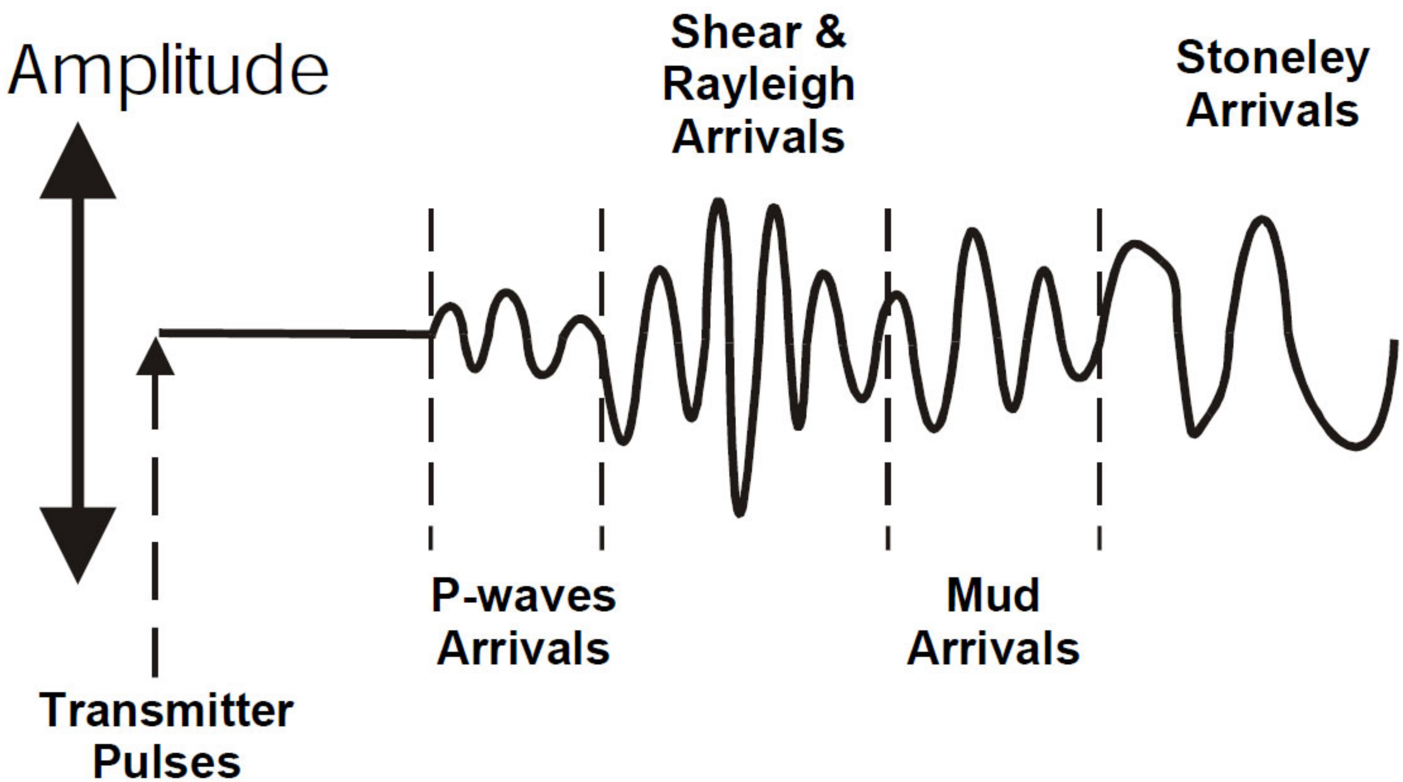
-dispertion

-attenuation

signal (t, A, sismogramme)

I. Introduction

➢ Train of vawes



$V\left[\frac{m}{s}\right]$ = P wave velocity

$\Delta t\ \left[\frac{s}{m}\ or\ \frac{microsec}{feet}\right]$ = Slowness

$$\Delta t = \frac{10^6}{V}$$

I. Introduction

➢ Wave velocity

The velocity and the slowness of the compressional wave depends upon the elastic properties of the rock (matrix + fluid) and to the density.

Slowness and velocity vary depending upon

- composition
- microstructure of the matrix,
- the type and distribution of the pore fluid
- the porosity of the rock.

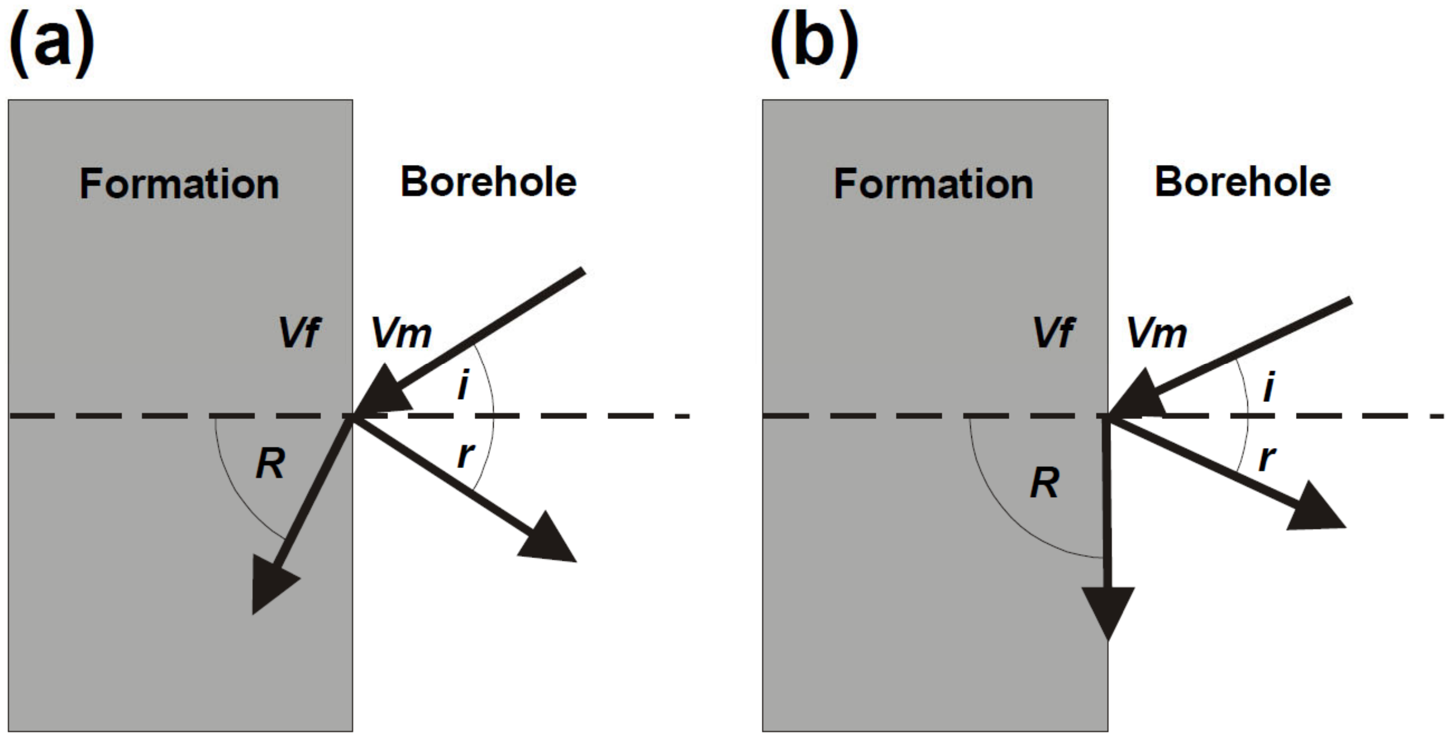
$$V \propto \frac{\text{Strength}}{\rho} \quad \text{and} \quad \Delta t \propto \frac{\rho}{\text{Strength}}$$

$$V_P = \sqrt{\frac{K + \frac{4}{3}\mu}{\rho}} \quad \text{for solids}$$

$$V_P = \sqrt{\frac{K}{\rho}} \quad \text{for fluids}$$

I. Introduction

➢ Reflection and Refraction : Snell's law



$$\frac{\sin i}{\sin R} = \frac{V_m}{V_f}$$

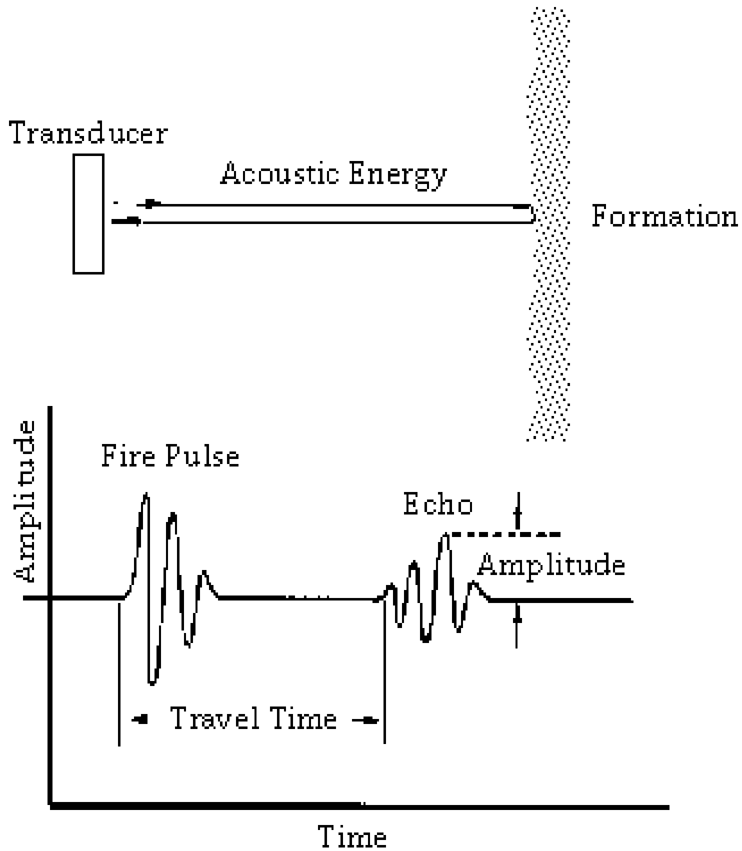
$$\sin i = \frac{V_m}{V_f}$$

m = mud
f = formation

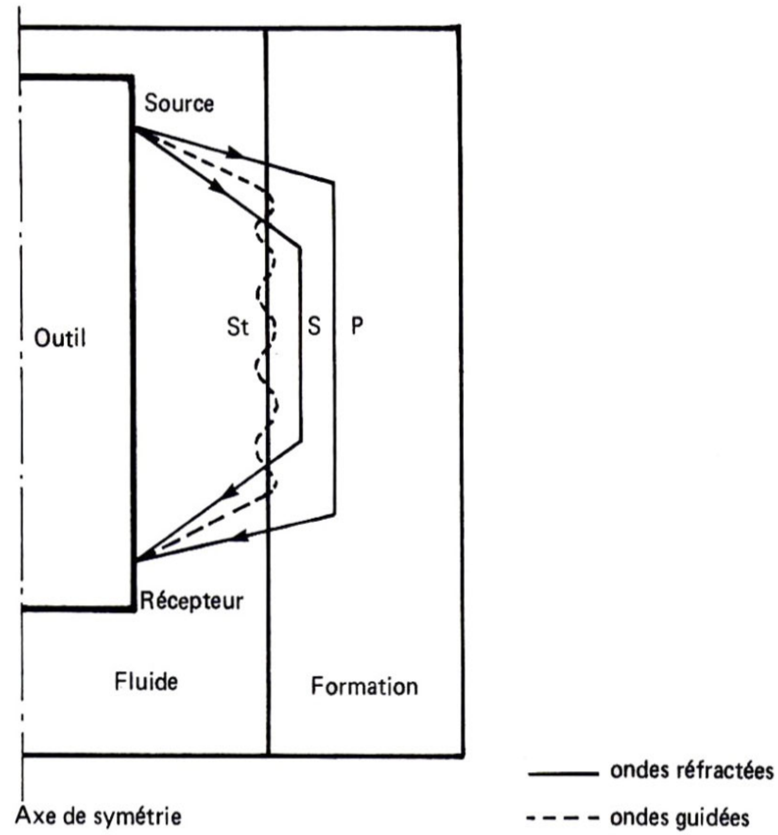
I. Introduction

➢ Reflection and Refraction

Images ➔ reflected waves



Sonic➔ refracted waves



I. Introduction

➢ Reflection and Refraction

RAPPEL DES DIFFÉRENTES BANDES DE FRÉQUENCES UTILISABLES POUR LES APPLICATIONS DE L'ACOUSTIQUE DES MILIEUX POREUX

Longueur d'onde en m pour $V = 4\,000$ m/s	4×10^2	40	4	0,4	4×10^{-2}	4×10^{-3}
Fréquences utilisées Hz	10	10^2	10^3	10^4	10^5	10^6
Type d'applications	Sismique d'exploration	Sismique de gisement		Diagraphie acoustique		Contrôle des matériaux
	Sismique basse fréquence					

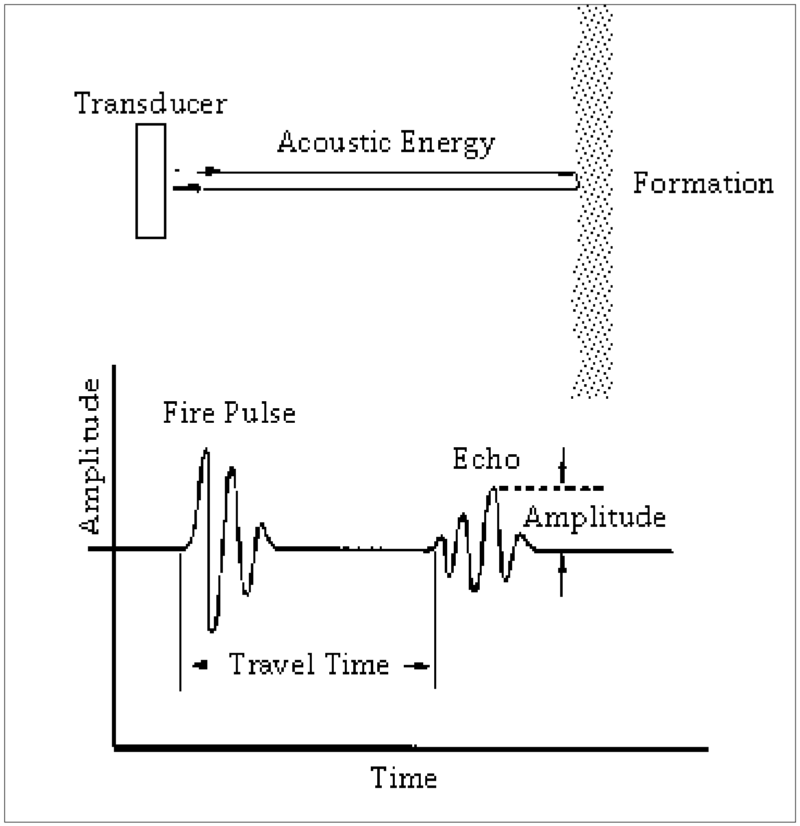
Acoustic methods : kHz ➔ MHz

wave length cm ➔ mm

(sonic ➔ image)

II. **Seismic imaging**

➢ Borehole imaging



Principle:

-Réflexion

-Fréquency ~ 200 - 500 kHz - MHz

➔ small penetration

➔ compromise between HR and attenuation (mud)

Measure = travel time + amplitude

- t ➔ borehole quality

- A ➔ impedance ➔ lithology

Acoustic impedance

$$Z = \rho V$$

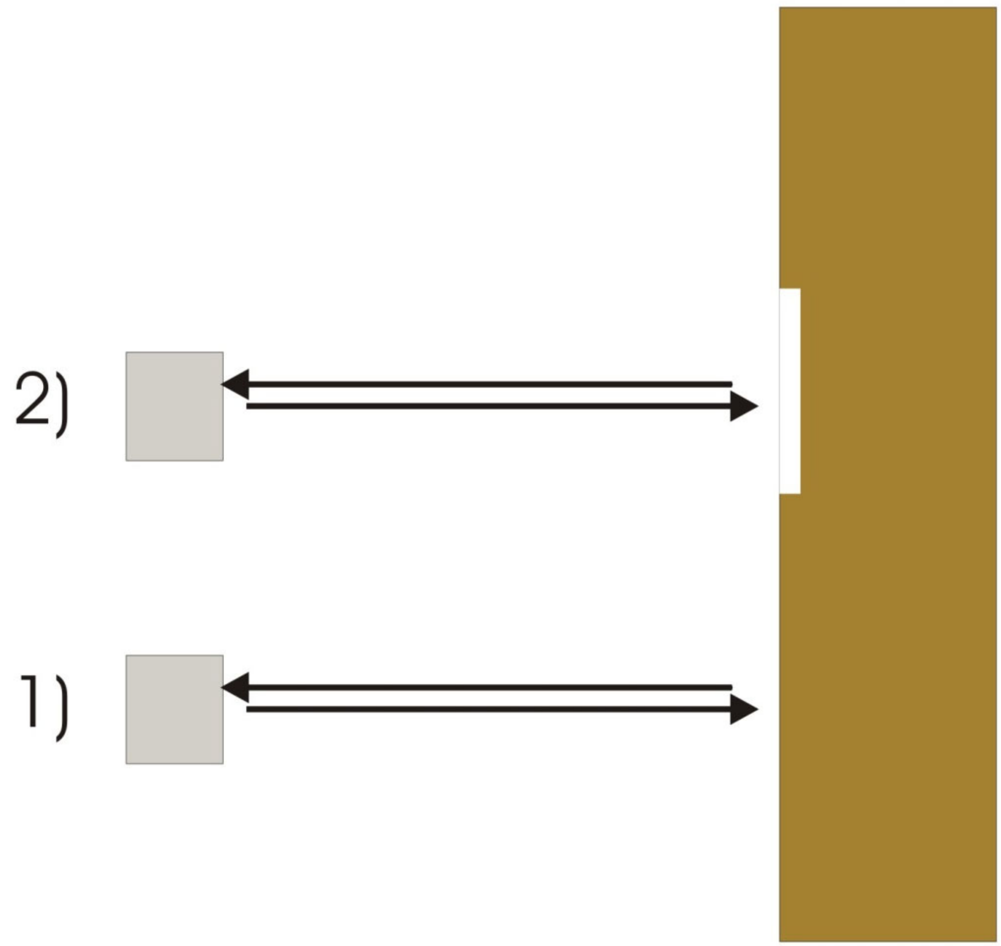
$$C_R \approx \frac{A_R^2}{A_i^2} \approx \frac{\rho_2 V_2 - \rho_1 V_1}{\rho_2 V_2 + \rho_1 V_1}$$

C_r= reflection coefficient/ impedance contrast

II. **Seismic imaging**

- Borehole imaging

t ➔ borehole quality



II. **Seismic imaging**

- Borehole imaging

A→ Impedance→ lithology

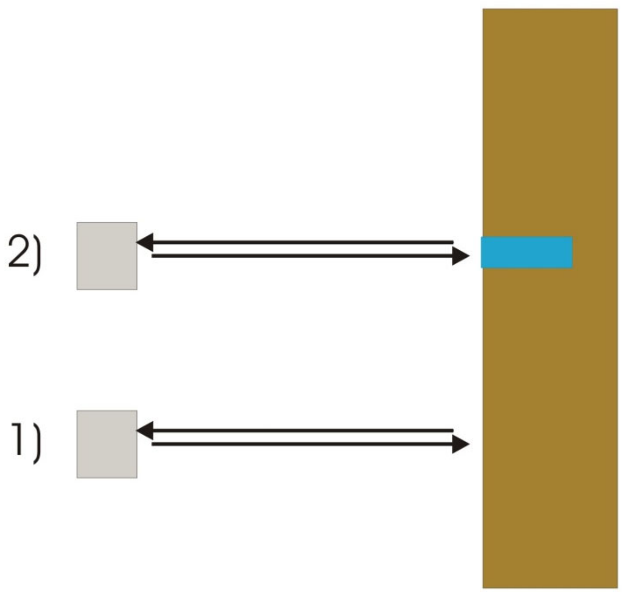
Table 2.3.2 Acoustic properties of some materials (modified from Hayman et al., 1991)

Material	Density ($kg \cdot m^{-3}$)	Acoustic velocity ($m \cdot s^{-2}$)	Acoustic impedance (MRayl) Pa. sec par m
Air (1-100 bar)	1.3 – 130	330	0.0004 – 0.04
Water	1000	1500	1.5
Drilling fluids	1000 – 2000	1300 – 1800	1.5 – 3.0
Shales	1900 – 2450	2300 – 3400	4.5 – 8.3
Sandstone (20 %)	2320	3900	9.0
Limestone (20 %)	2370	4200	10.0
Dolomite (20 %)	2520	4950	12.5
Anhydrite	2960	6100	18

II. **Seismic imaging**

- Borehole imaging

A➔ Impedance➔ lithology



$$Z = \rho V$$

$$C_R = \frac{A_R^2}{A_i^2}$$

Example: open fracture

-Decrease of impedance contraste

-Internal reflexion➔ attenuation

II. **<u>Seismic imaging</u>**

- Loggings problems

- Bad borehole quality

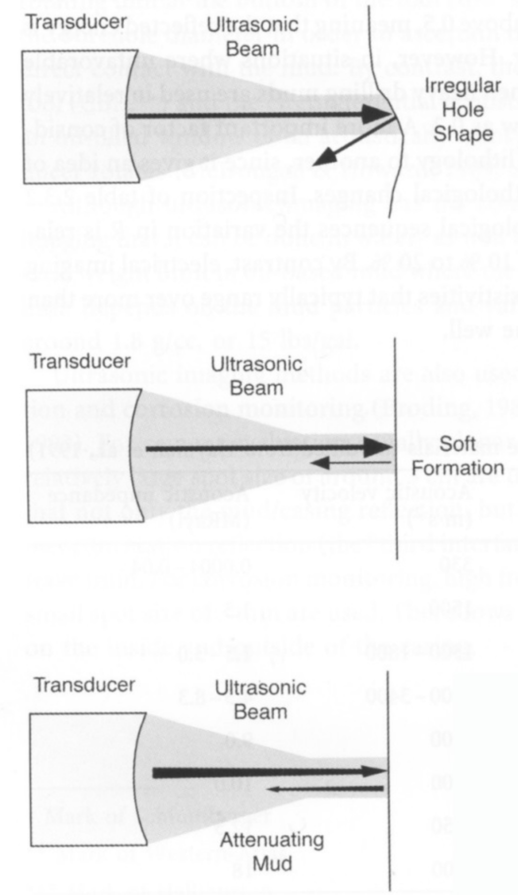
➔ Othogonal refection

-Soft formation

➔Low amplitude

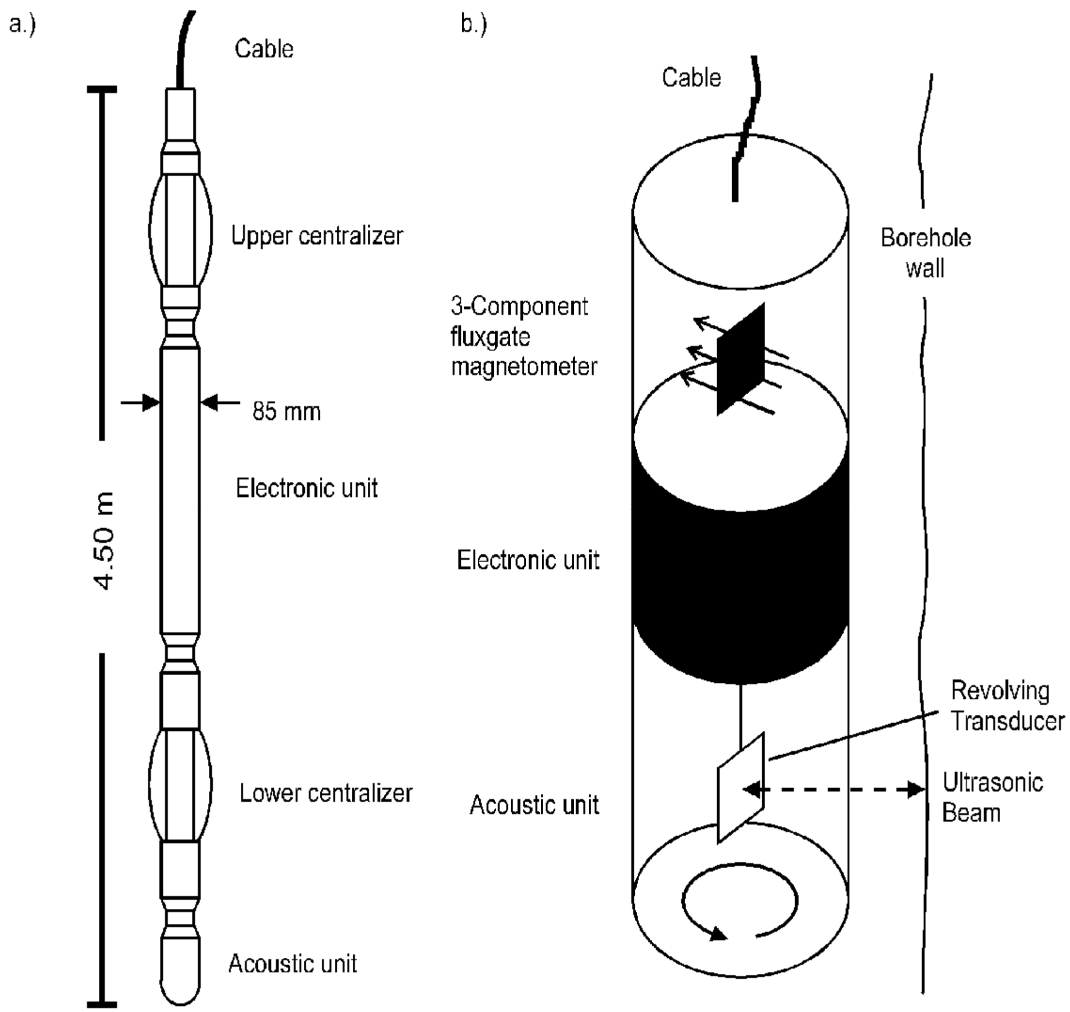
-Mud presence

➔ Low amplitude



II. Seismic imaging

➢ Methods



engine

600 tr/s ➔ 1°

Magnetometer

➔ Orientation

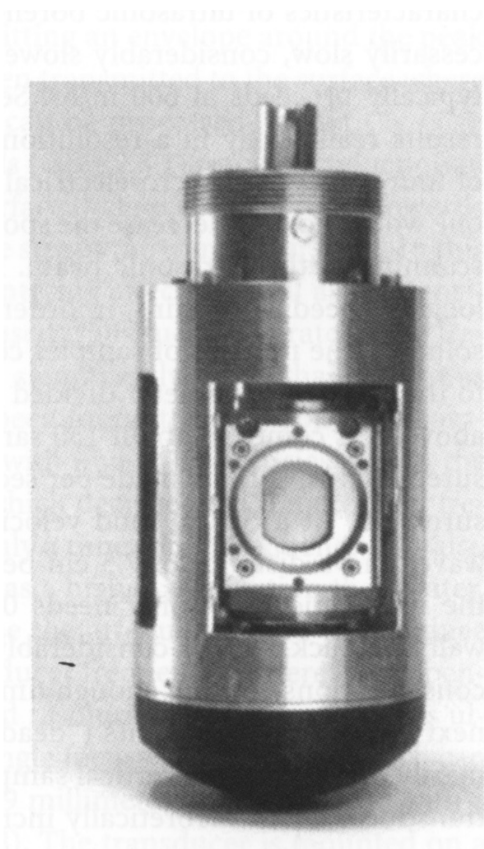
Émetteur - Récepteur

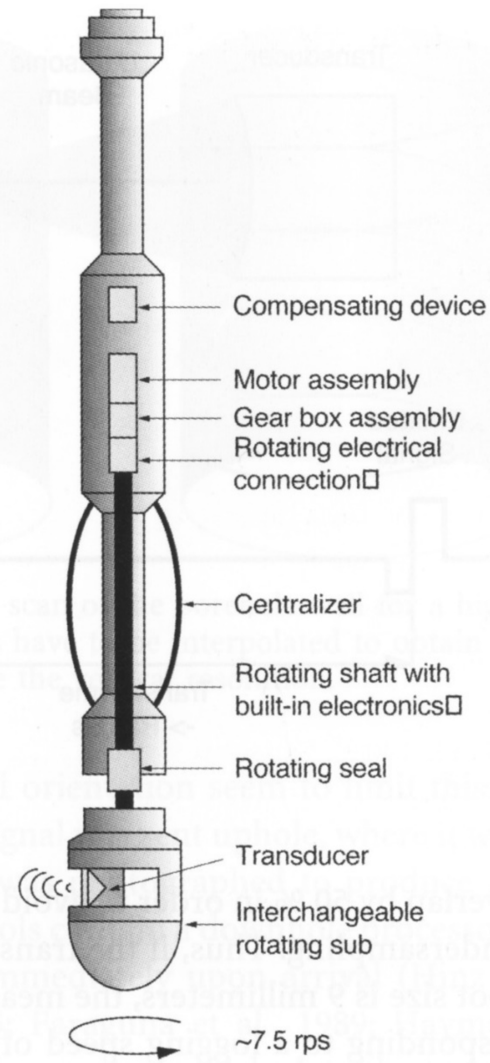
BHTV: Borehole Teleseismic Viewer (1960)

II. **Seismic imaging**

- Methods

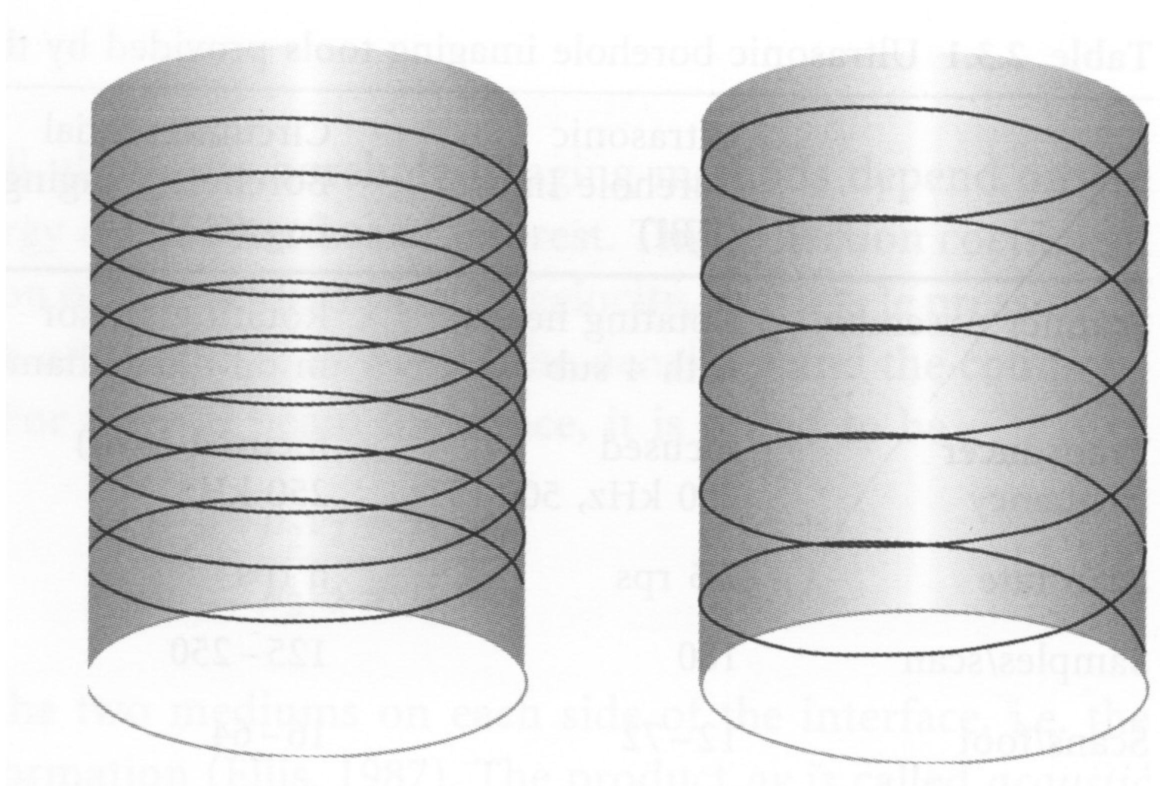
- UBI:Ultrasonic Borehole Image





II. **Seismic imaging**

➢ Methods

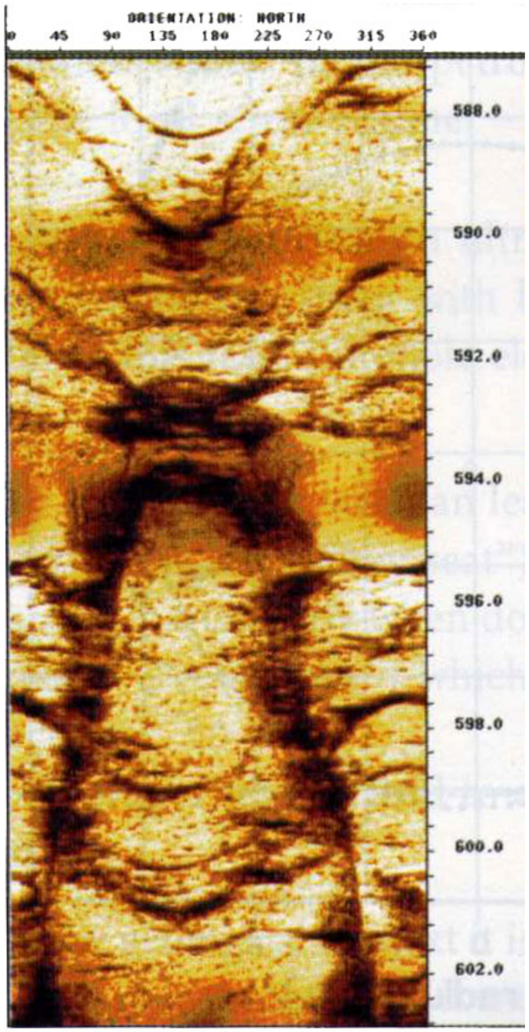


Spiral displacement

(spot ~2 cm - 400 à 2100 m/hr)

II. **Seismic imaging**

➢ Methods



- Borehole imaging

↓

- Ultrasonic Scanner

↓

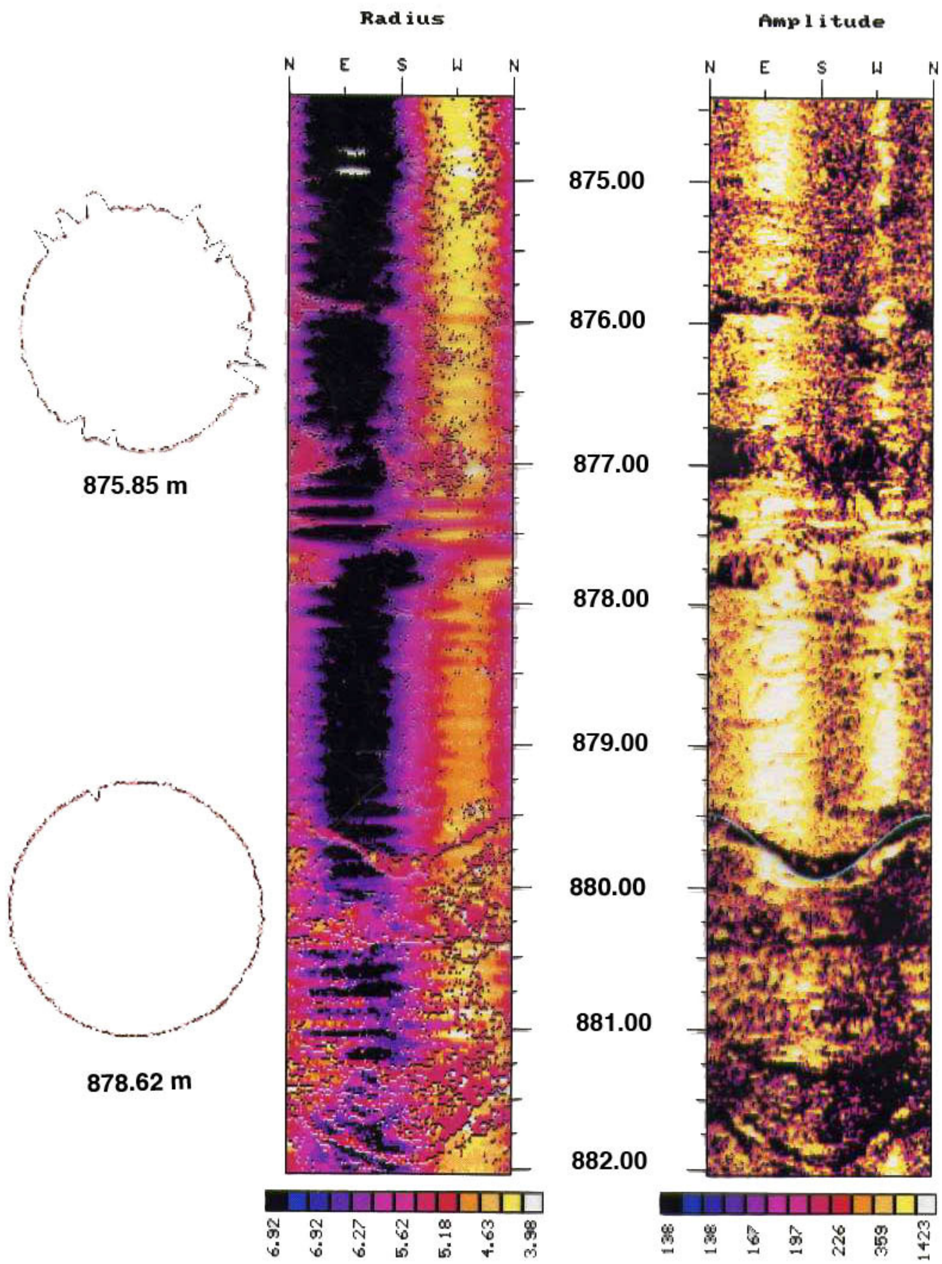
Fractures

borehole quality

Lithology / Texture

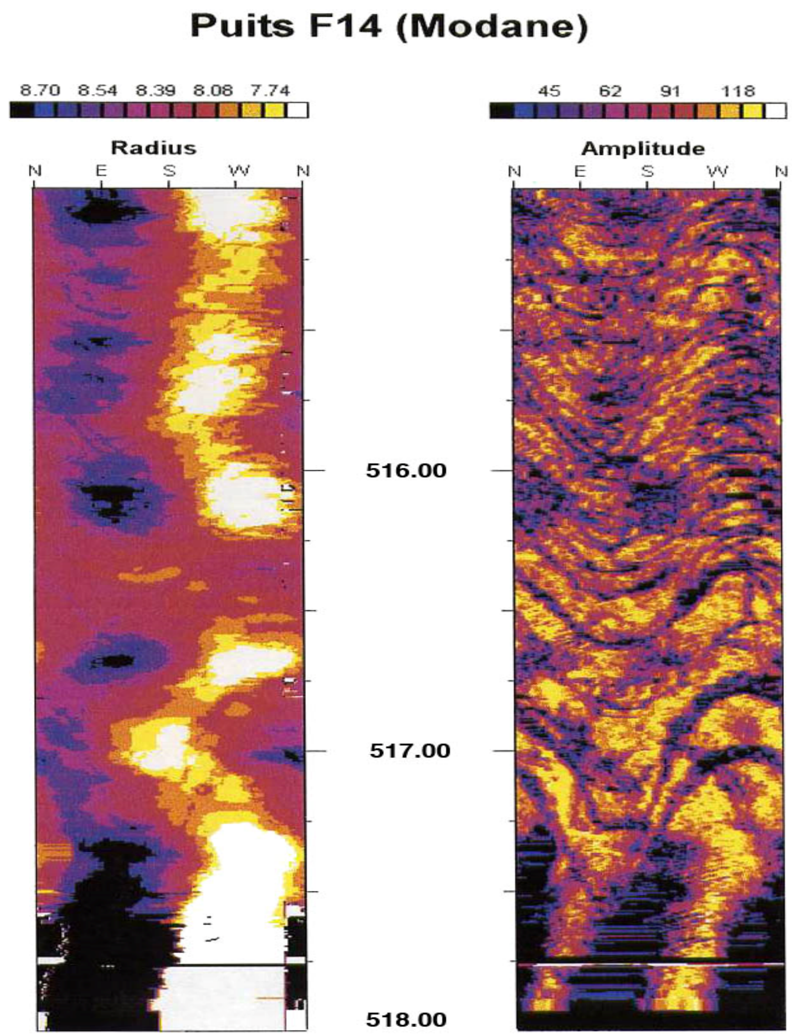
II. Seismic imaging

- Methods



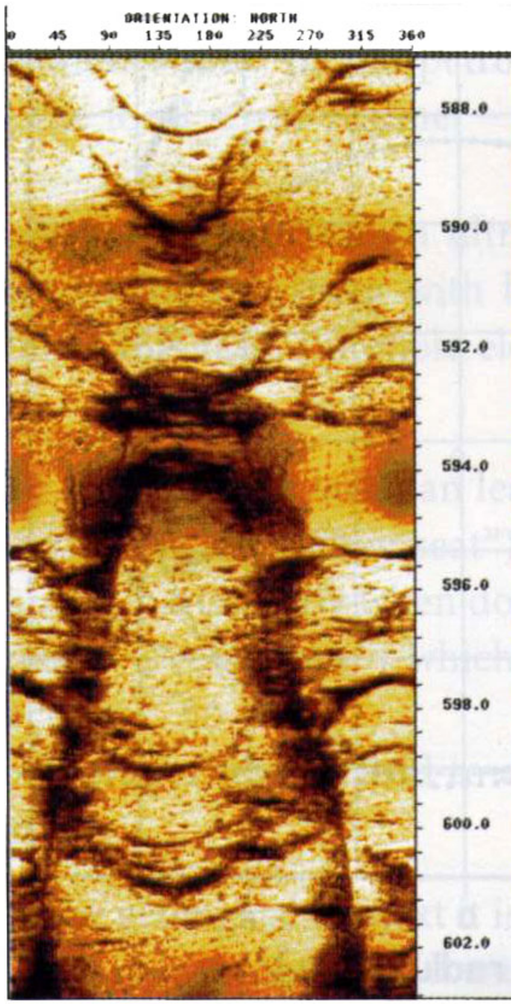
II. **Seismic imaging**

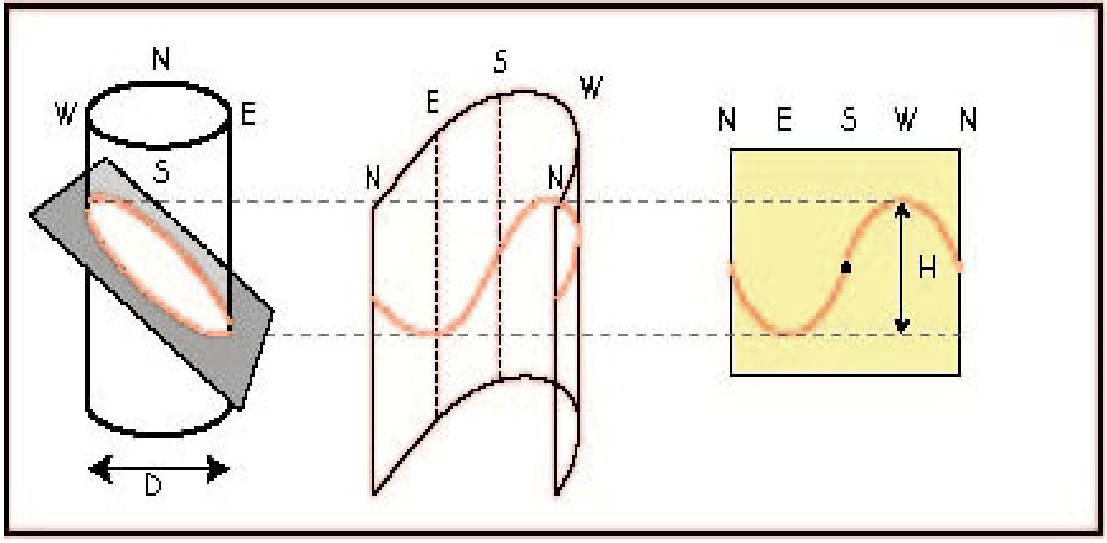
- Methods



II. Seismic imaging

➢ Image interpretation





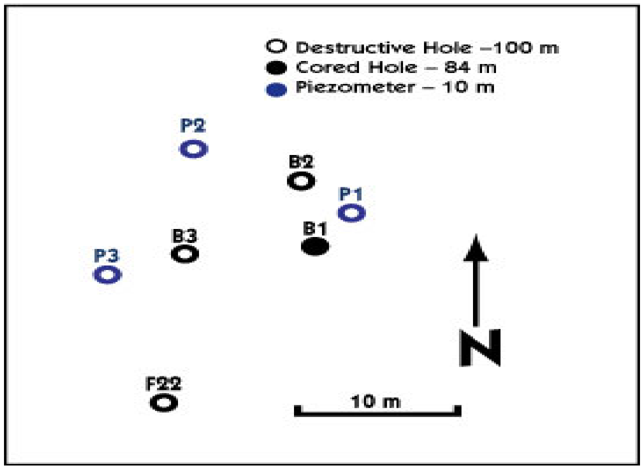
$$Dip = \tan^{-1}\left(\frac{H}{D}\right)$$

Lowest point = dip direction

II. **Seismic imaging**

➢ Example

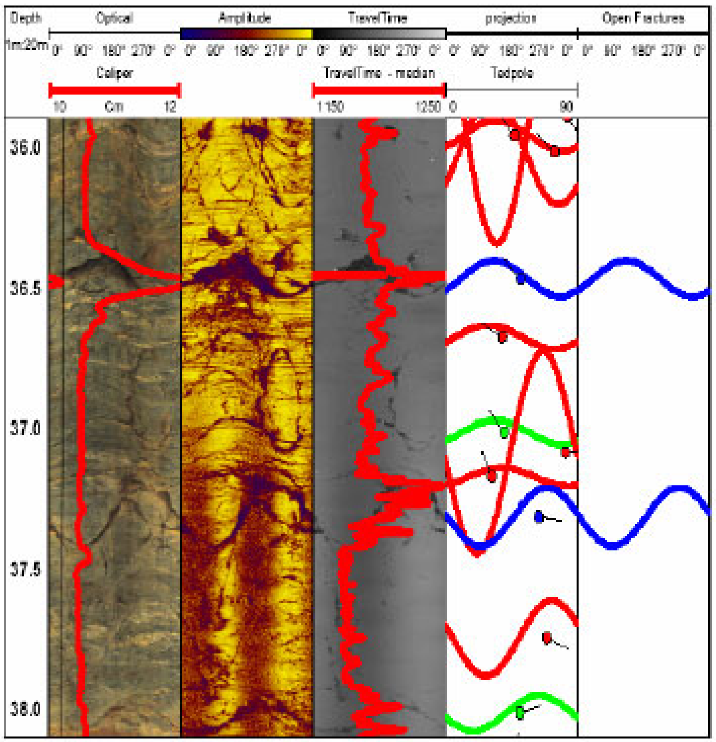
- Ploemeur (Bretagne) : hydrologic reservoir

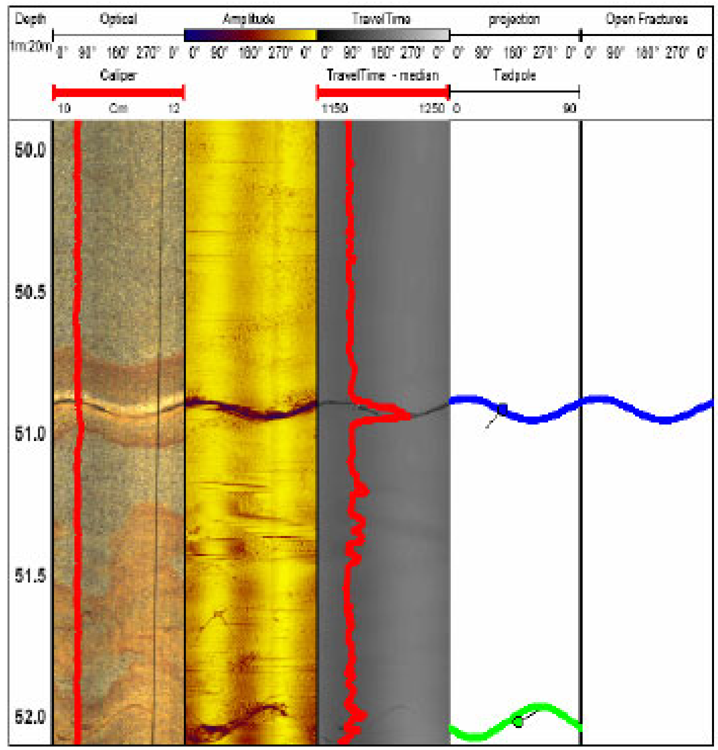


II. **<u>Seismic imaging</u>**

➢ <u>Example</u>

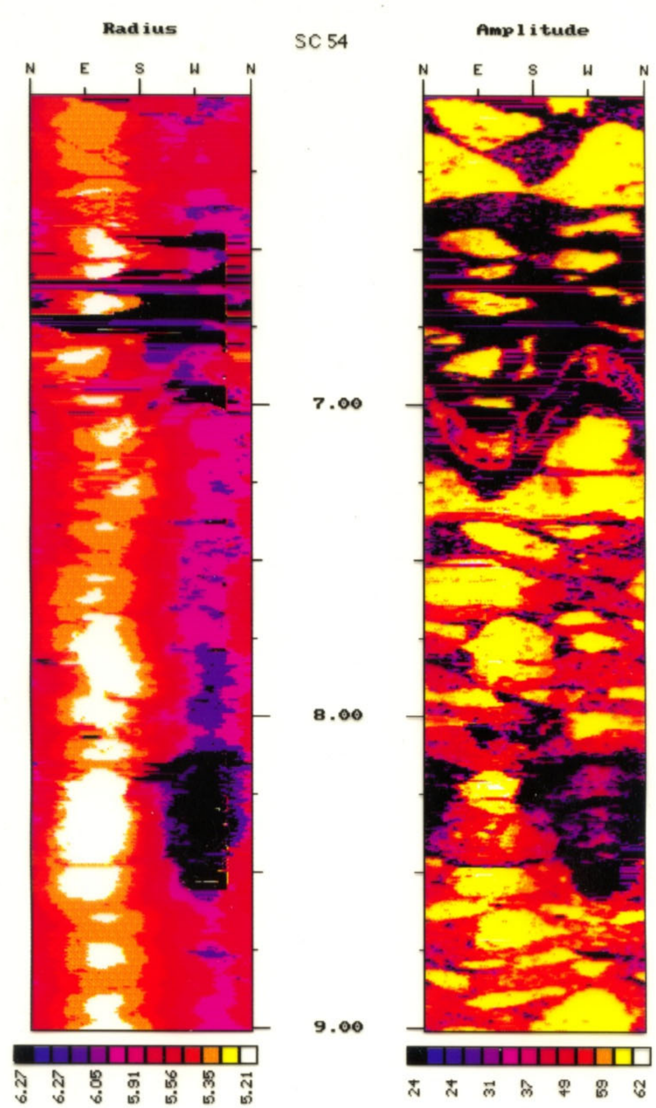
Open/ close fracture





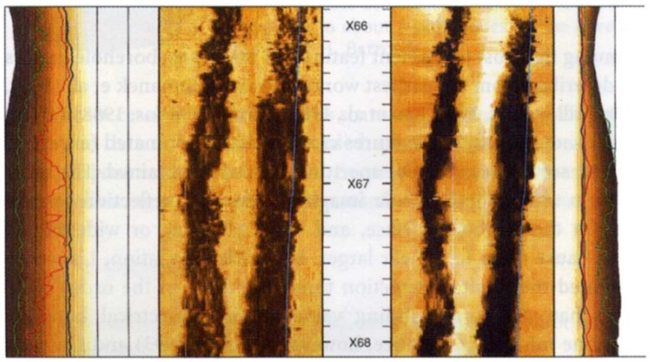
II. **Seismic imaging**

➢ Commercial port of Marseille



II. **Seismic imaging**

➢ Commercial port of Marseille



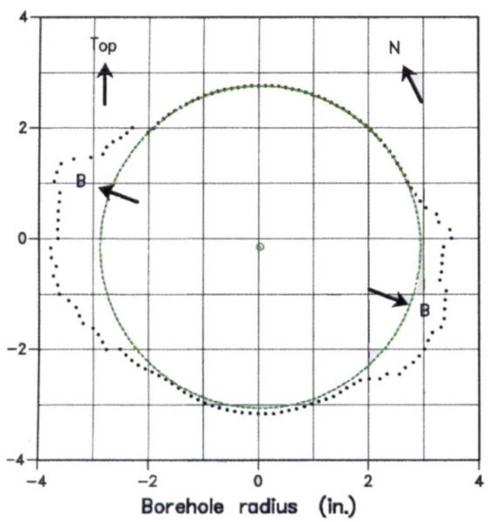
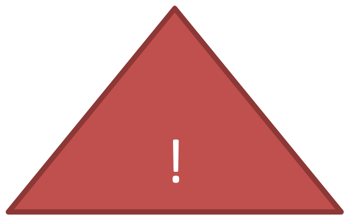


Figure 2.3.11. Breakouts seen on the reflected amplitude and transit tine images (top) and in a borehole cross-section constructed from a transit time scan (bottom). Notice slight azimuthal rotation with overall E-W direction of the breakouts.

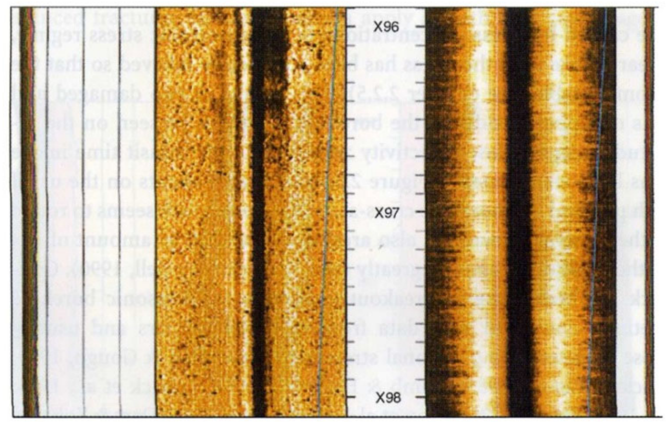
Interpretation of breakouts :
-Lower amplitude
➔ Stress field
➔ σ_{Hmin}= direction of breakout

II. **Seismic imaging**



Borehole ovalisation
➔ lower amplitude

➔ Due to drilling



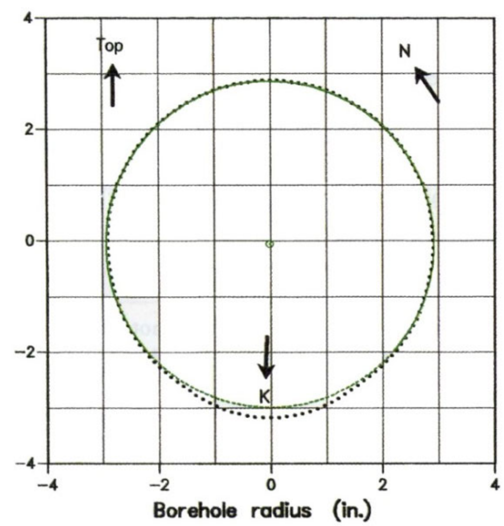


Figure 2.3.12. A borehole elongation due to key seating seen on the reflected amplitude and transit time images (top) and in a borehole cross-section constructed from the transit time image (bottom). The elongation is at the bottom of the hole and probably caused by drill pipe wear on the rock.

II. **Seismic imaging**

Displacement of the borehole center

➔ fault zone

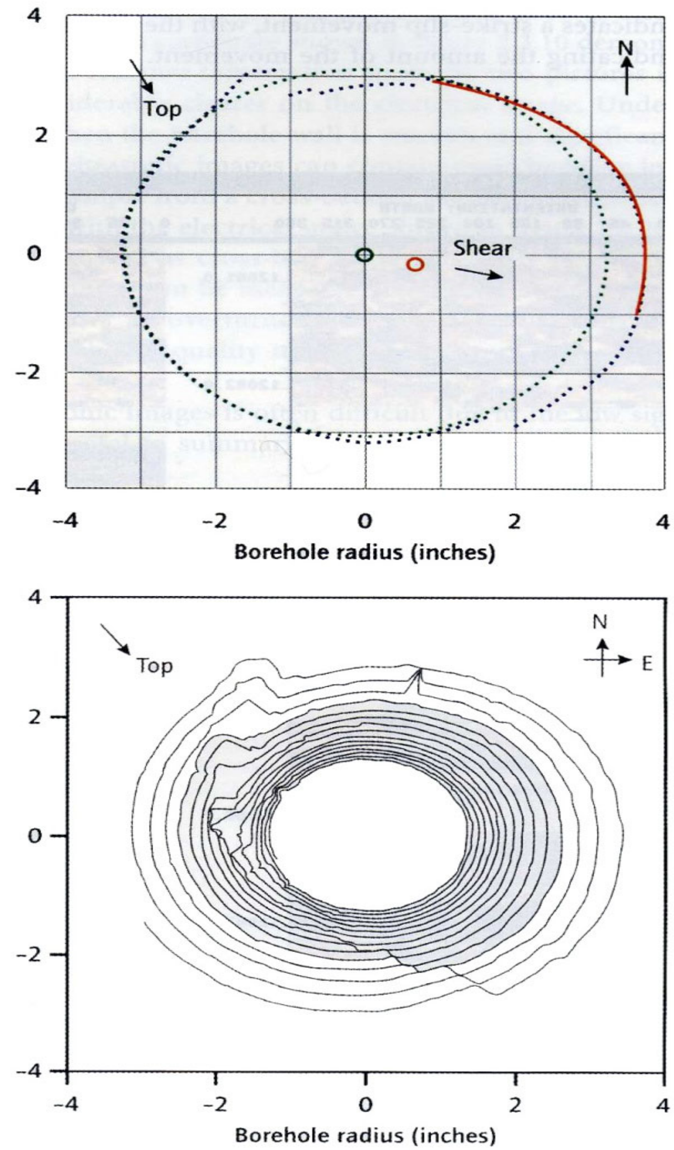
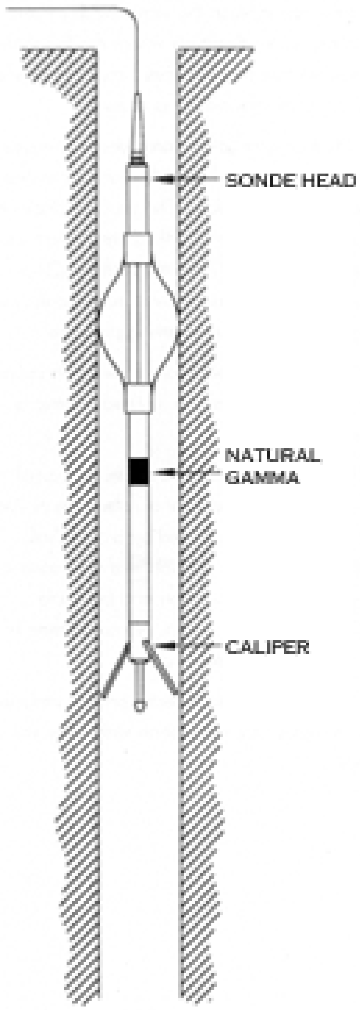
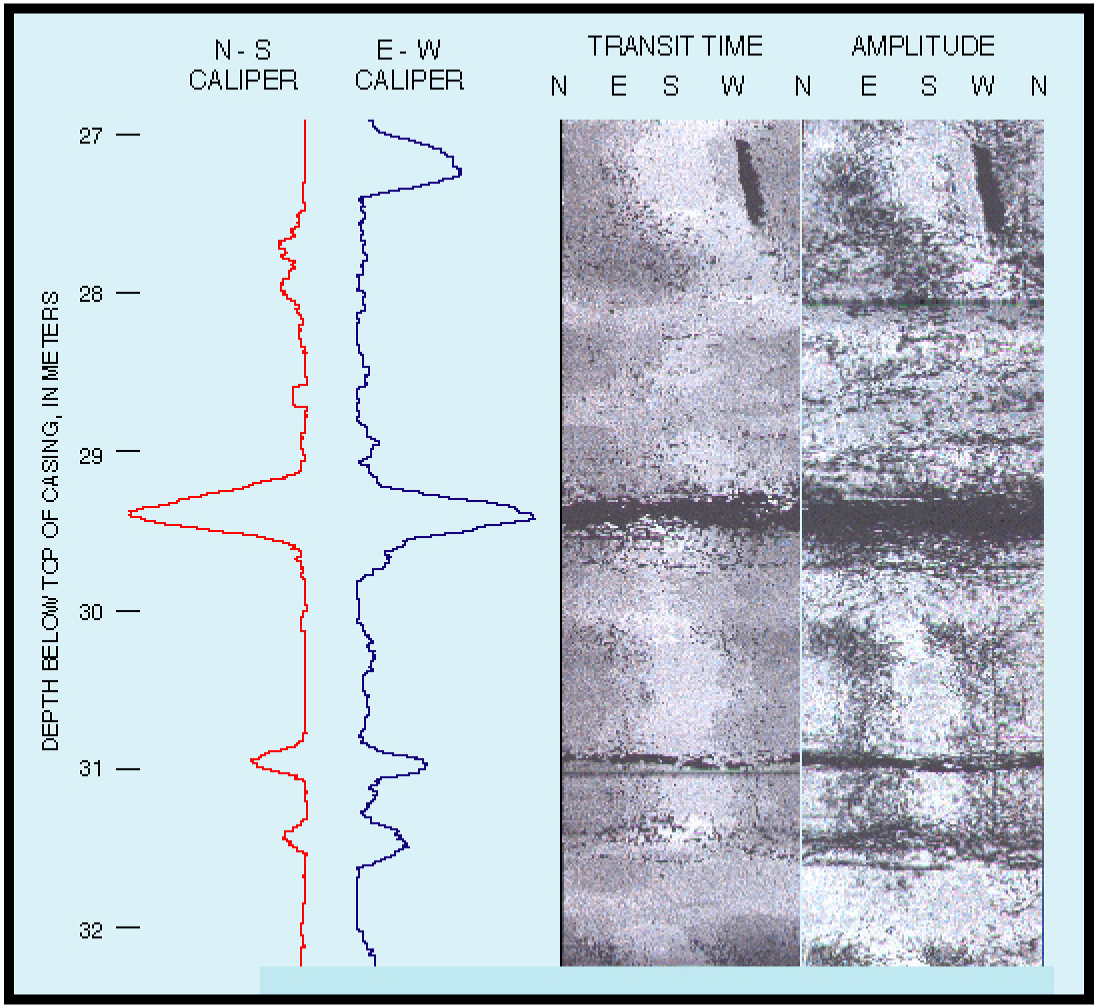


Figure 2.3.13. A borehole affected by strike-slip movement during drilling. The cross-section shows that two circles of equal radius but with offset centers can be fitted. This offset corresponds to the amount of slippage in the horizontal direction (after Hayman et al., 1998).

II. **Seismic imaging**

- Tools



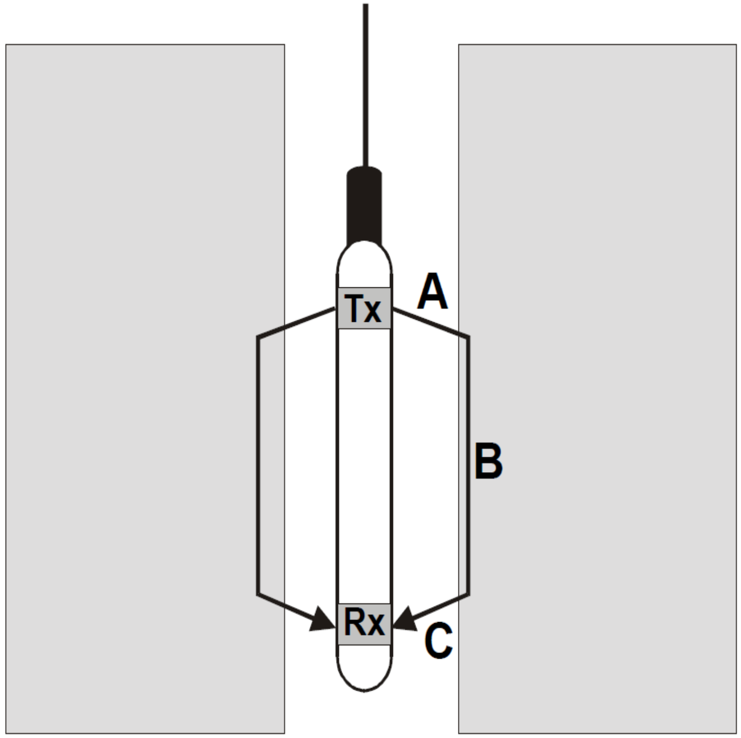


III. Sonic method

➢ Early tools

Early tools had one Tx and one Rx. The body of the tool was made from rubber (low velocity and high attenuation material) to stop waves travelling preferentially down the tool to the Rx. There were two main problems with this tool:

- The measured travel time was always too long because the time taken for the elastic waves to pass through the mud was included in the measurement. The measured time was A+B+C rather than just B.
- The length of the formation through which the elastic wave traveled (B) was not constant because changes to the velocity of the wave depending upon the formation altered the critical refraction angle.



Transmitter (Tx)
Receiver (Rx)

III. **Sonic method**

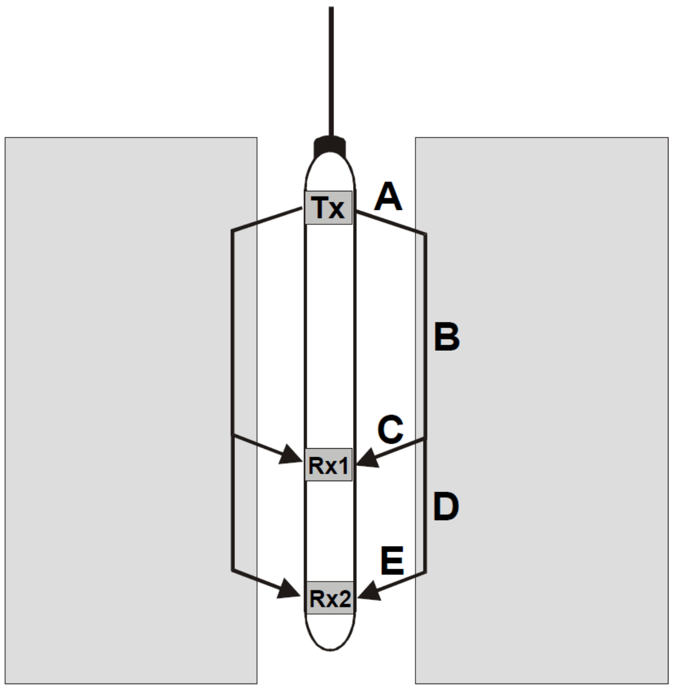
➢ Dual Receiver Tools

- These tools were designed to overcome the problems in the early tools. They use two receivers a few feet apart, and measure the ***difference*** in times of arrival of elastic waves at each Rx from a given pulse from the Tx . This time is called the ***sonic interval transit time*** (Δt) and is the time taken for the elastic wave to travel through the interval D (i.e., the distance between the receivers).
- The time taken for elastic wave to reach Rx1: $\boldsymbol{TR_{x1} = A+B+C}$
- The time taken for elastic wave to reach Rx2: $\boldsymbol{TR_{x2} = A+B+D+E}$
- The **sonic interval transit time** :

$\boldsymbol{\Delta T = (TR_{x2} - TR_{x1}) = A+B+D+E - (A+B+C) = D+E-C.}$

- *If tool is axial in borehole: C = E,*

so $\Delta T = (TRx2 - TRx1) = D$

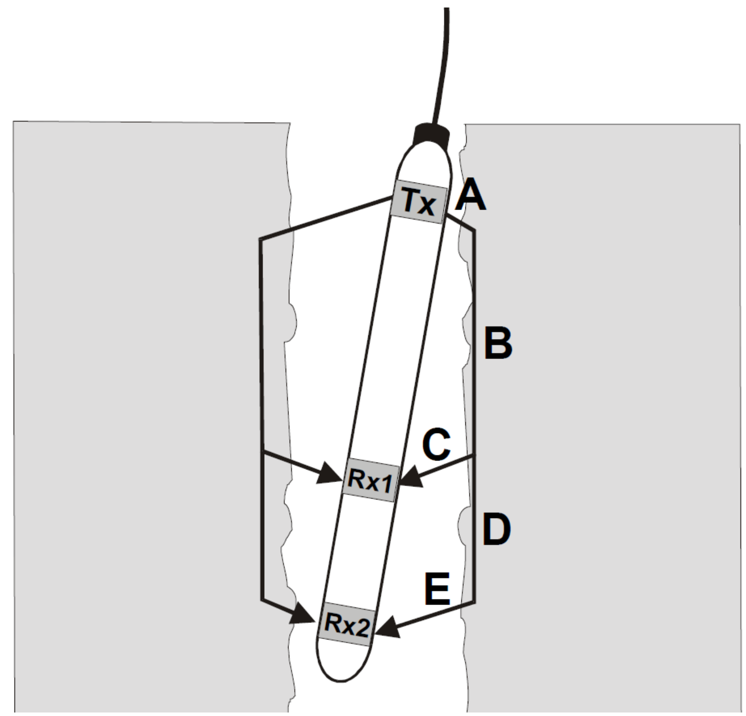


Transmitter (Tx)
Receiver (Rx)

III. **Sonic method**

➢ Dual Receiver Tools

The problem with this arrangement is that if the tool is tilted in the hole, or the hole size changes (Fig. 16.6), we can see that C≠E, and the two Rx system fails to work.



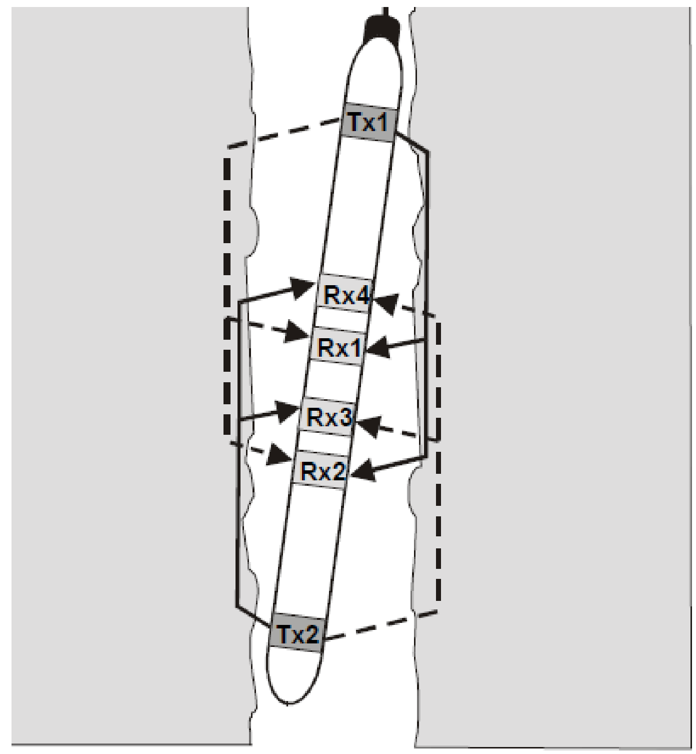
Transmitter (Tx)
Receiver (Rx)

III. **Sonic method**

- Borehole Compensated Sonic (BHC) Tool

This tool compensates automatically for problems with tool misalignment and the varying size of the hole. It has **two transmitters and four receivers,** arranged in two dual receiver sets, but with one set inverted (i.e., in the opposite direction). Each of the **transmitters is pulsed alternately**, and Δt values are measured from alternate pairs of receivers. These two values of Δt are then averaged to compensate for tool misalignment, at to some extent for changes in the borehole size.

Pulse duration= 100-200 µs with a gap of 20s = 20 pulse / sec

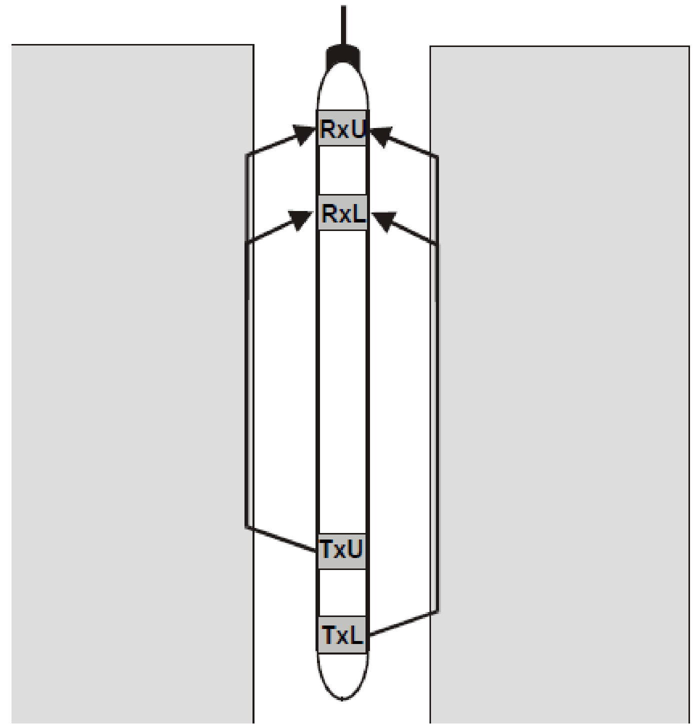


Transmitter (Tx)
Receiver (Rx)

III. **Sonic method**

- Long spacing sonic (lss) tools

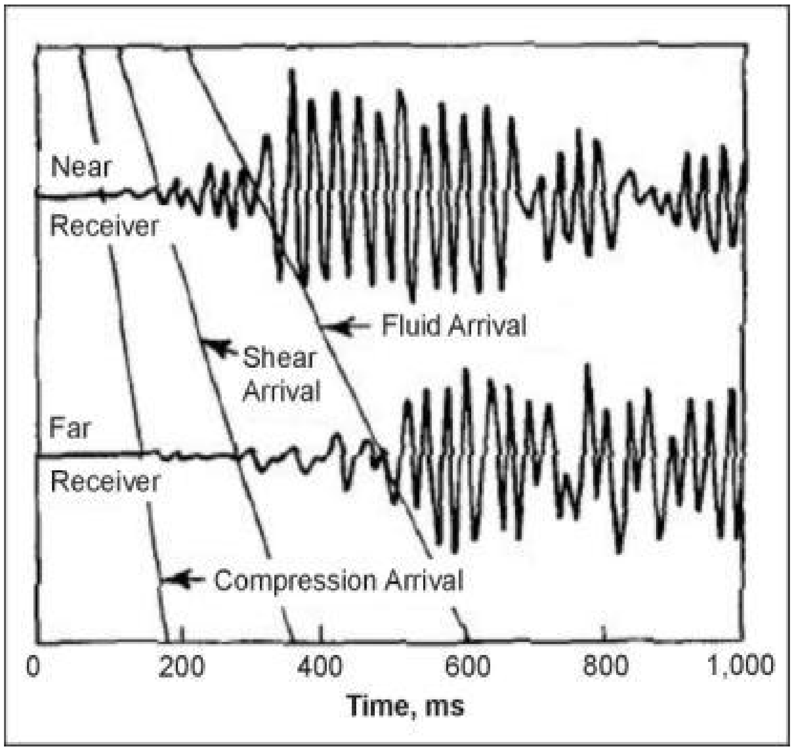
It was recognized that in some logging conditions a longer Tx-Rx distance could help.
Give two readings: near reading and far reading

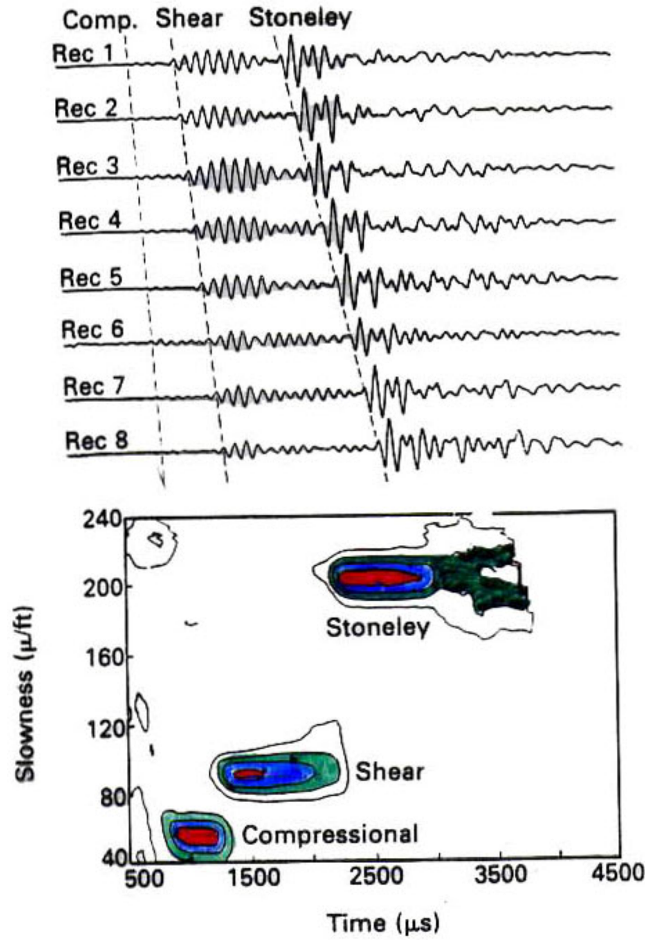


Transmitter (Tx)
Receiver (Rx)

III. **Sonic method**

➢ Long spacing sonic (lss) tools





V_P: 5 km/s - V_S: 3 km/s -V_{St}: 1.5 km/s

III. **Sonic method**

➢ Calibrations

- The tool is calibrated inside the borehole opposite beds of pure and known lithology, such as anhydrite, salt , or inside the casing (57.1 ms/ft.).

III. **Sonic method**

- Depth of investigation

- In theory, the refracted wave travels along the borehole wall, and hence the **depth of penetration is small** (2.5 to 25 cm). It is independent of Tx- Rx spacing, but depends upon the wavelength of the elastic wave, with larger wavelengths giving larger penetrations.
- As wavelength $l = V/f$ (i.e., velocity divided by frequency), for any given tool frequency, the higher the velocity the formation has, the larger the wavelength and the deeper the penetration.

III. **<u>Sonic method</u>**

- Vertical resolution, and logging speed

- The vertical resolution is equal to the Rx-Rx spacing.

- The typical logging speed for the tool is 1500 m/hr), although it is occasionally run at lower speeds to increase the vertical resolution.

III. **Sonic method**

➢ Loggings problems

- **Electrical Noise**

- Δt **Stretch** (in heavily attenuating formations the value of Δt can be slightly too large)

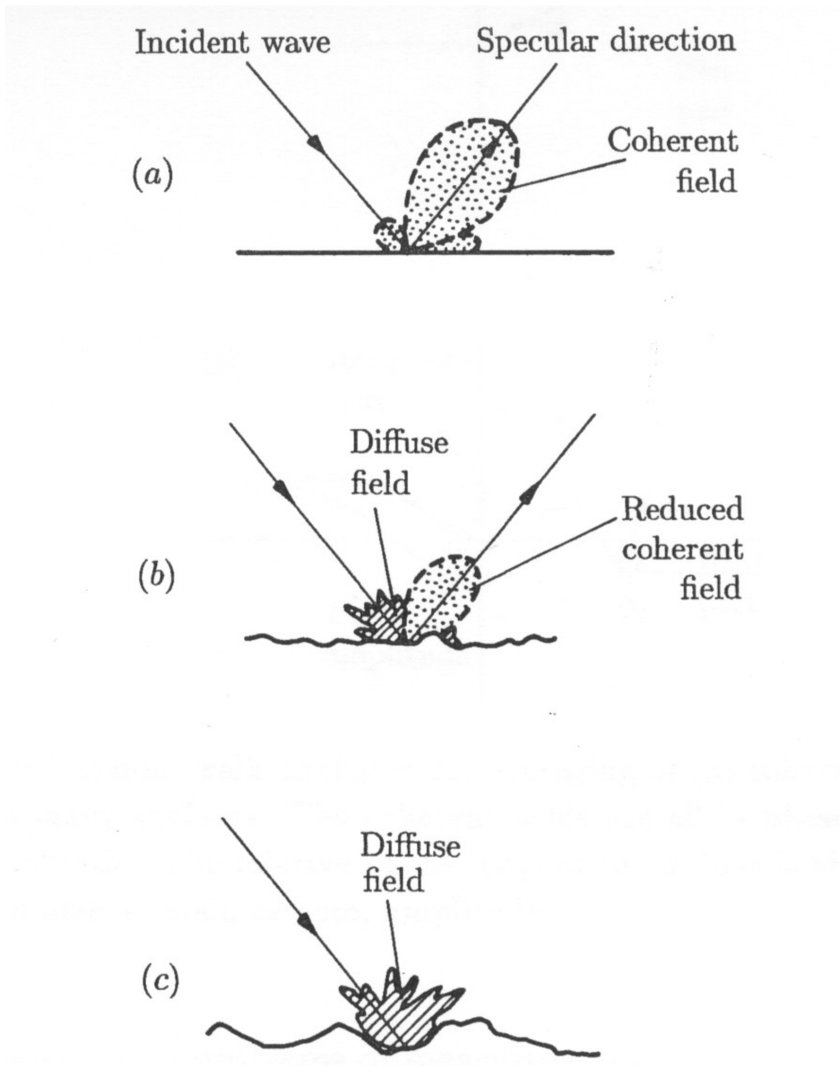
- **Mud arrivals** : first arrival should be from a P-wave that has traveled through the formation. In some circumstances the P-wave that has traveled directly through the mud arrives first.

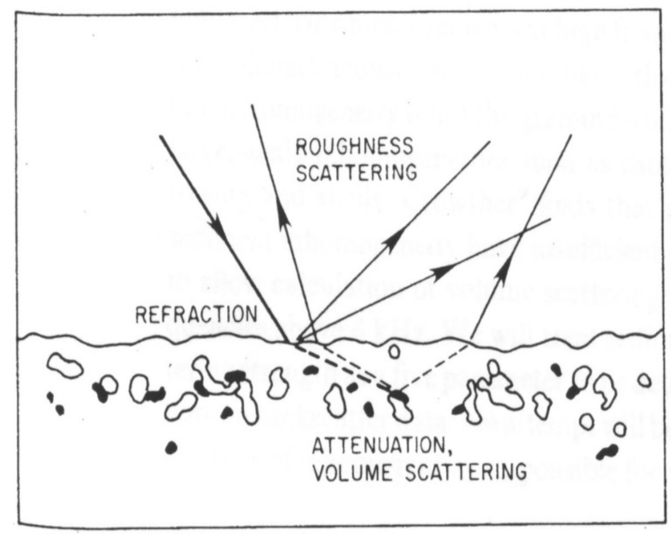
- **Altered Zone Arrivals** : The formation next to the borehole may not be typical of the rock. For example, it may be filled with solid mud and have a higher velocity than the virgin formation, or it may be fractured or altered and have a lower velocity. (lss, beter performance in this case)

- **Borehole roughness**

III. **Sonic method**

- Borehole surface roughness





III. **Sonic method**

- Use of seismic log

Seismic data calibration

Seismic interval velocities

Synthetic seismograms

Porosity determination

Stratigraphic correlation

Identification of lithologies

Compaction

Overpressure

III. **Sonic method**

➢ Porosity determination

$$\frac{1}{V} = \frac{\phi}{V_P} + \frac{(1-\phi)}{V_{ma}}$$

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

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

Material	Δt (µs/ft.)	V (ft./s)	V (m/s)
Compact sandstone	55.6 – 51.3	18000 – 19500	5490 – 5950
Limestone	47.6 – 43.5	21000 – 23000	6400 – 7010
Dolomite	43.5 – 38.5	23000 – 26000	7010 – 7920
Anhydrite	50.0	20000	6096
Halite	66.7	15000	4572
Shale	170 – 60	5880 – 16660	1790 – 5805
Bituminous coal	140 – 100	7140 – 10000	2180 – 3050
Lignite	180 – 140	5560 – 7140	1690 – 2180
Casing	57.1	17500	5334
Water: 200,000 ppm, 15 psi	180.5	5540	1690
Water: 150,000 ppm, 15 psi	186.0	5380	1640
Water: 100,000 ppm, 15 psi	192.3	5200	1580
Oil	238	4200	1280
Methane, 15 psi	626	1600	490

Δt = transit time in the formation of interest

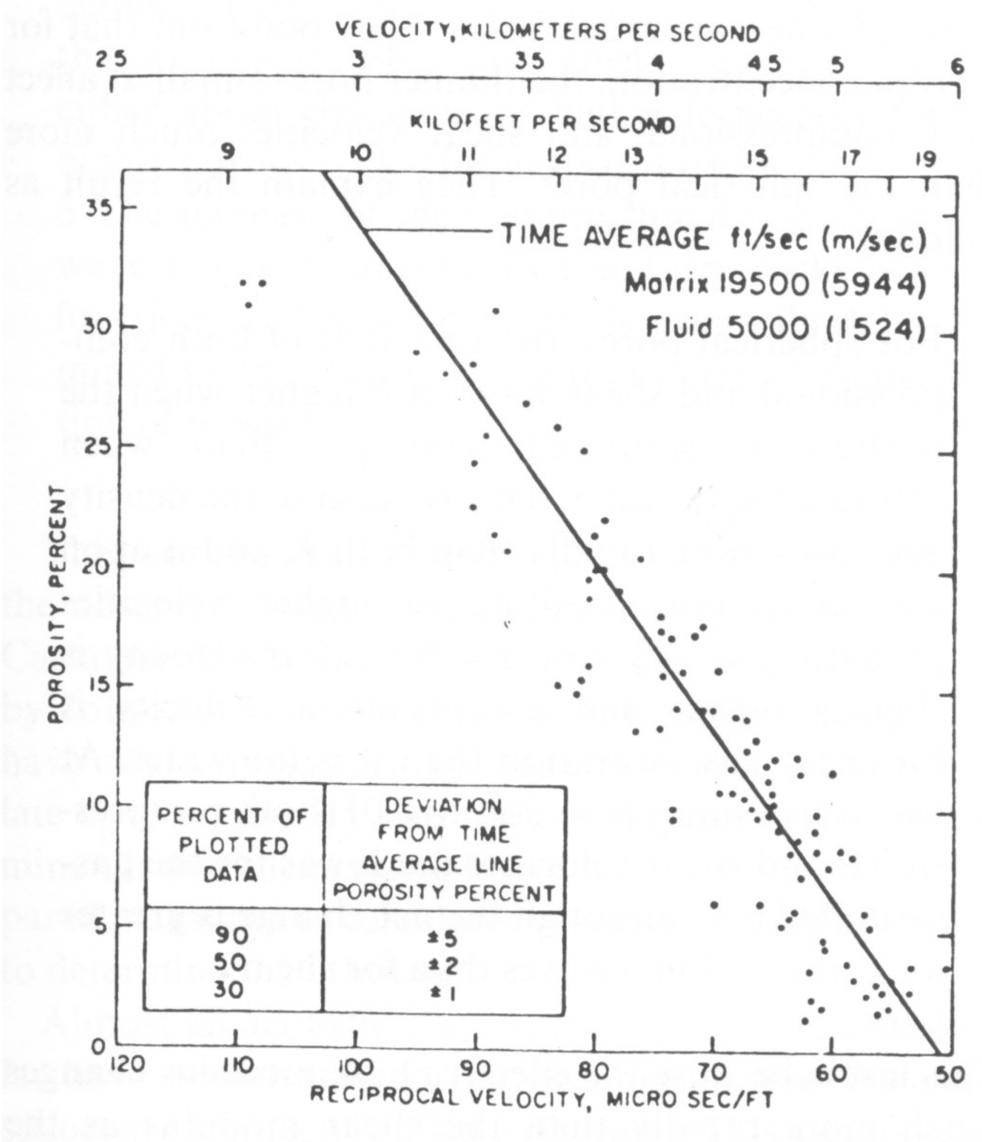
Δt_p = the transit time through 100% of the pore fluid

Δt_{ma} = the transit time through 100% of the rock matrix

ϕ = porosity

III. **<u>Sonic method</u>**

- <u>Porosity determination</u>



III. **Sonic method**

➢ Porosity determination

Porosity are overestimated in uncompacted formation (shale). An empirical correction *Bcp* is then applied:

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

→ B_{cp} approximately equal to the value of D*t* in the adjacent shales divided by 100.

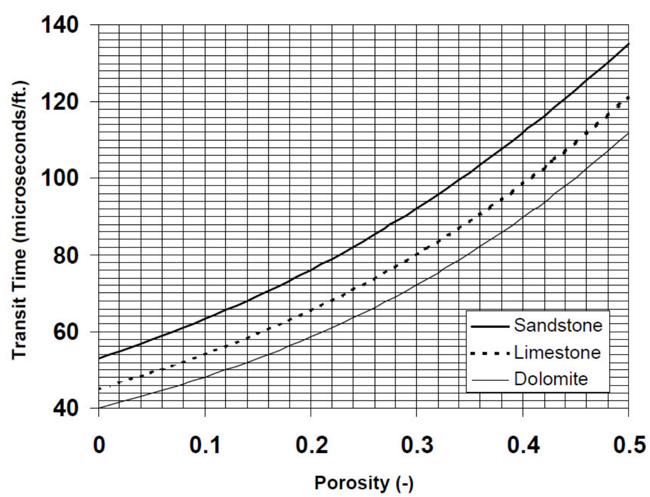
III. **<u>Sonic method</u>**

➢ <u>Porosity determination</u>

Another method for calculating the porosity from the sonic log was proposed by Raymer. This is expressed as:

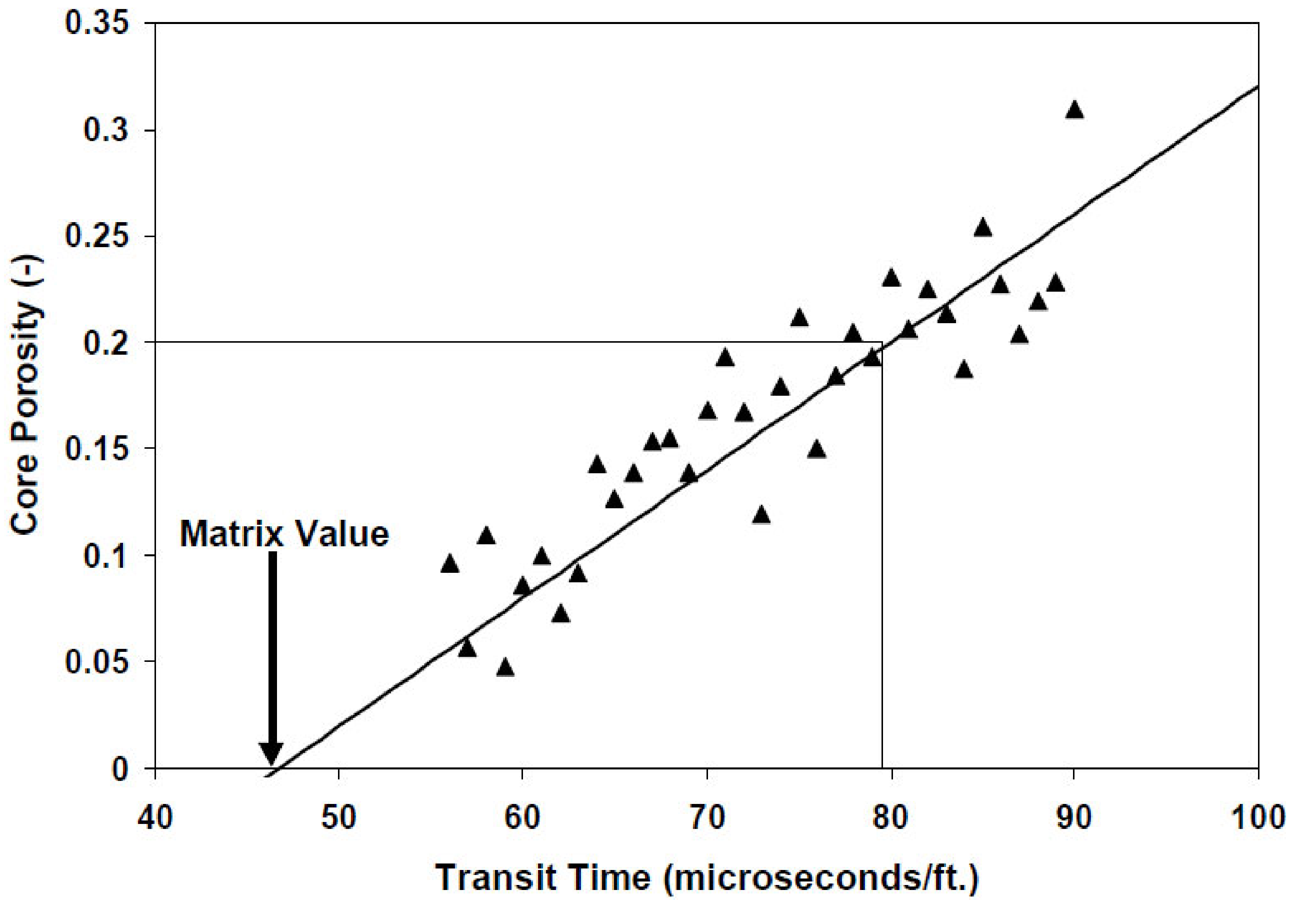
$$\frac{1}{\Delta t} = \frac{\phi}{\Delta t_p} + \frac{(1-\phi)^2}{\Delta t_{ma}}$$

This provides a much superior accuracy porosity over the entire range of geologically reasonable Δt.



III. **Sonic method**

➢ Calibration against core



III. **Sonic method**

➢ Effect of shale on the sonic derived porosity

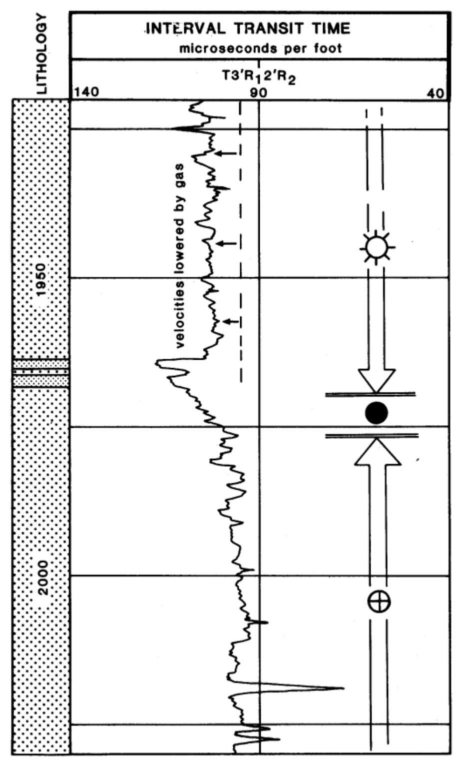
The effect of shales is very variable. This is because is depends upon the density of the shales, which varies a lot.

- Young shales ~under-compacted ➔low density➔ increase transit time ➔ slightly higher sonic derived porosities.
- Ancient compact shales ~high density, tending ➔ lower transit time ➔ smaller porosities.

III. **<u>Sonic method</u>**

- <u>Effect of gas on the sonic derivied porosity</u>

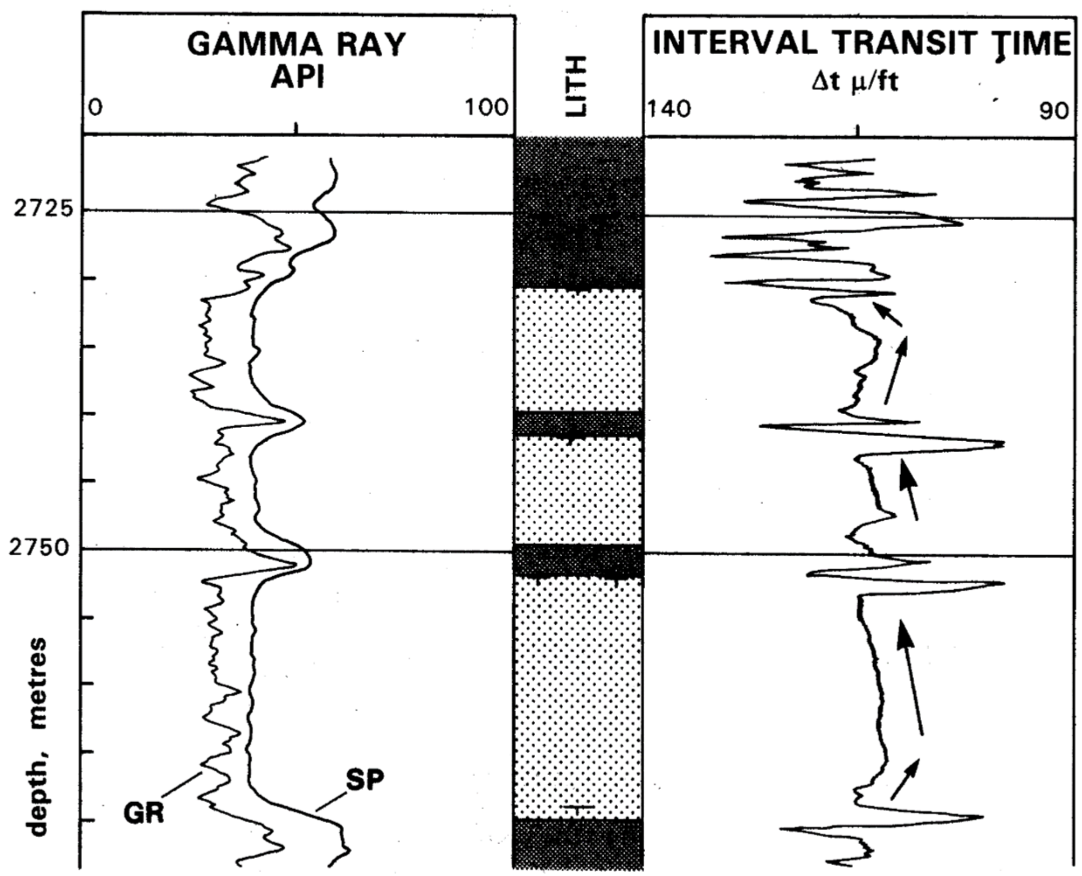
Gas has a low density, and hence decreases the apparent density of a formation if present. This causes an increase in the sonic transit time, and hence a porosity that is overestimated.



III. **Sonic method**

- Stratigraphic correlation

The sonic log is sensitive to small changes in grain size, texture, mineralogy, carbonate content, quartz content as well as porosity. This makes it a very useful log for using for correlation and facies analysis.

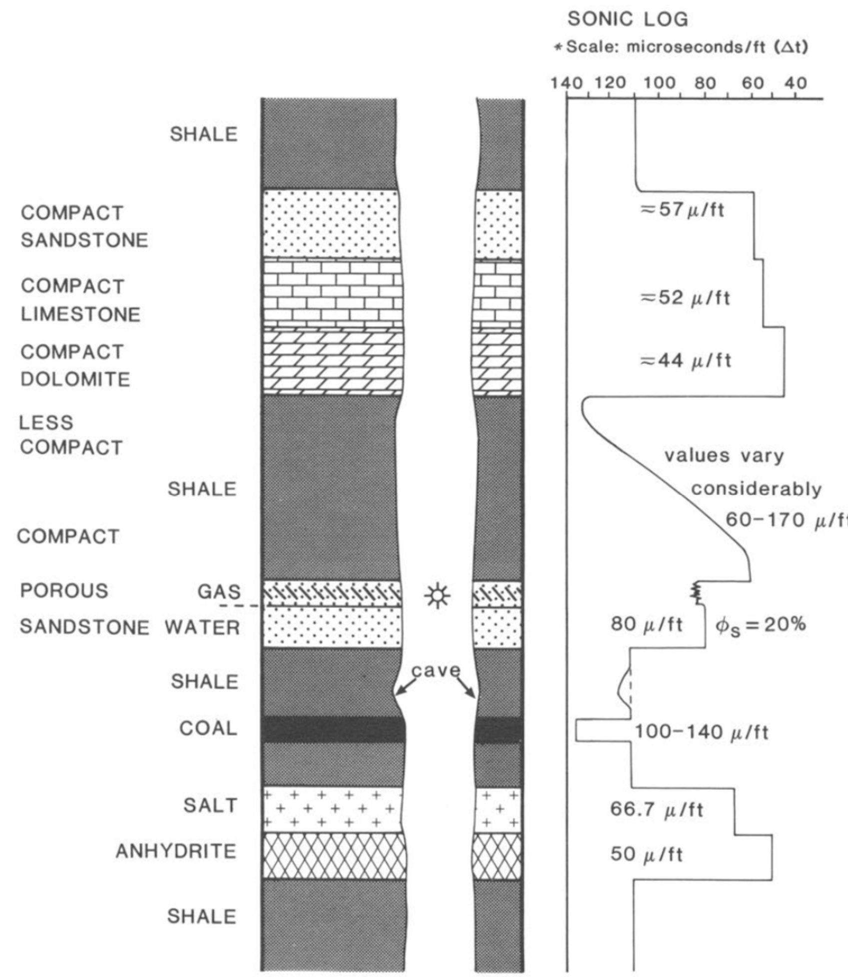


III. **Sonic method**

- Identification of Lithologies

The velocity or interval travel time is rarely diagnostic of a particular rock type. However, high velocities usually indicate carbonates, middle velocities indicate sands and low velocities, shales.

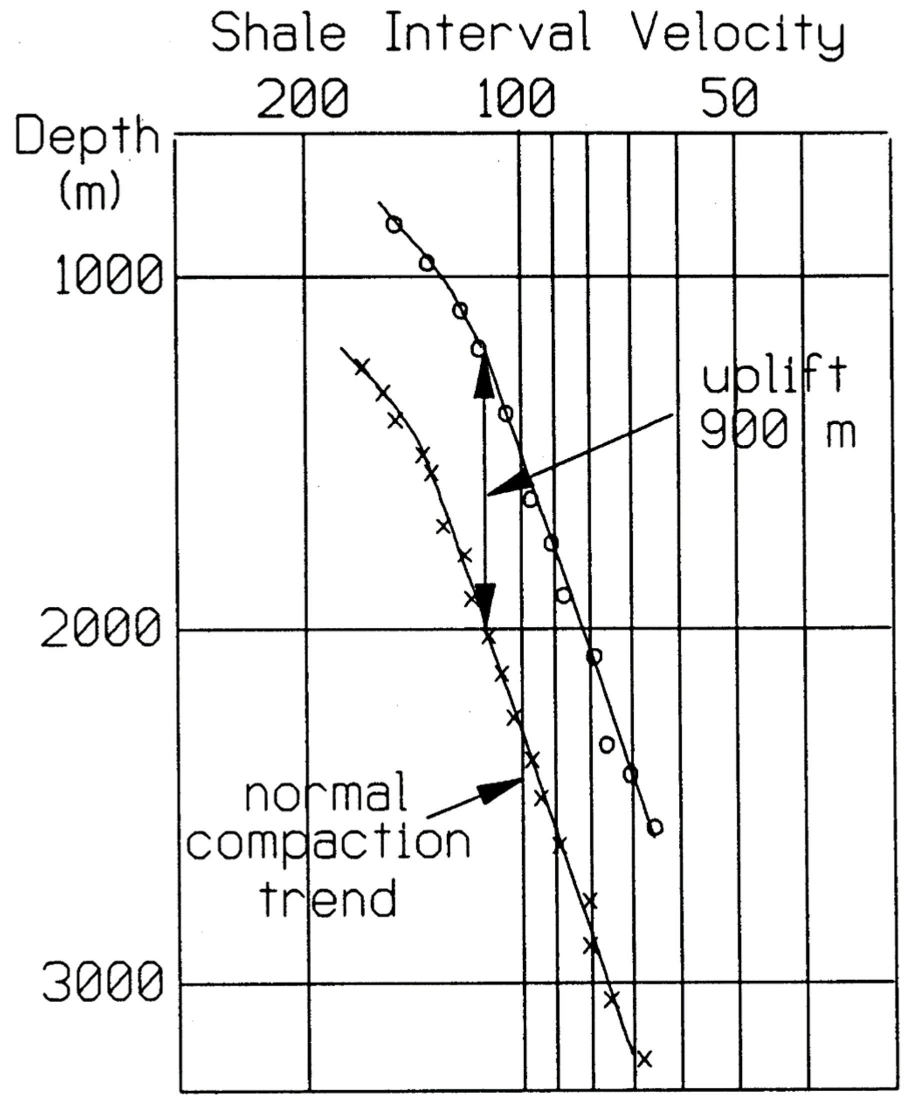
It is best to use the sonic log with other logs if lithological identification is important.



III. **<u>Sonic method</u>**

➢ <u>Compaction</u>

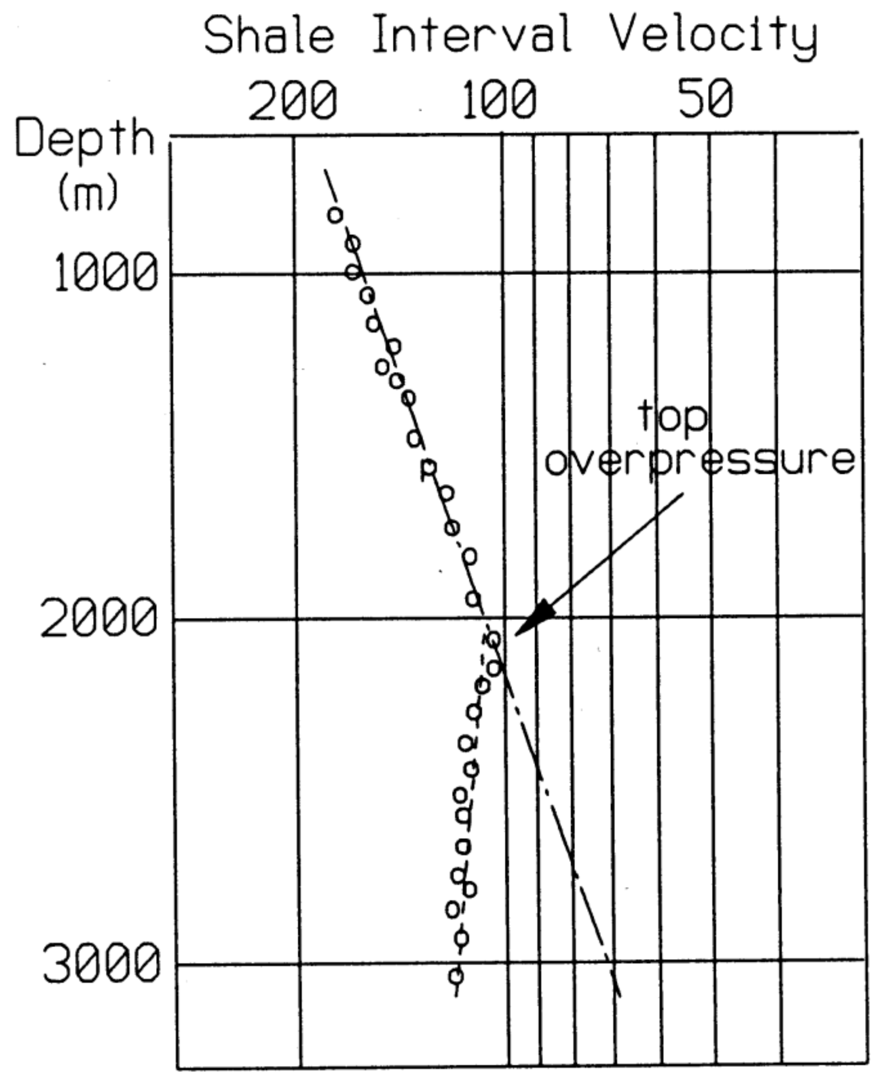
As a sediment becomes compacted, the velocity of elastic waves through it increases. If one plots theinterval transit time on a logarithmic scale against depth on a linear scale, a straight line relationship emerges. This is a compaction trend.



III. **Sonic method**

➢ Overpressure

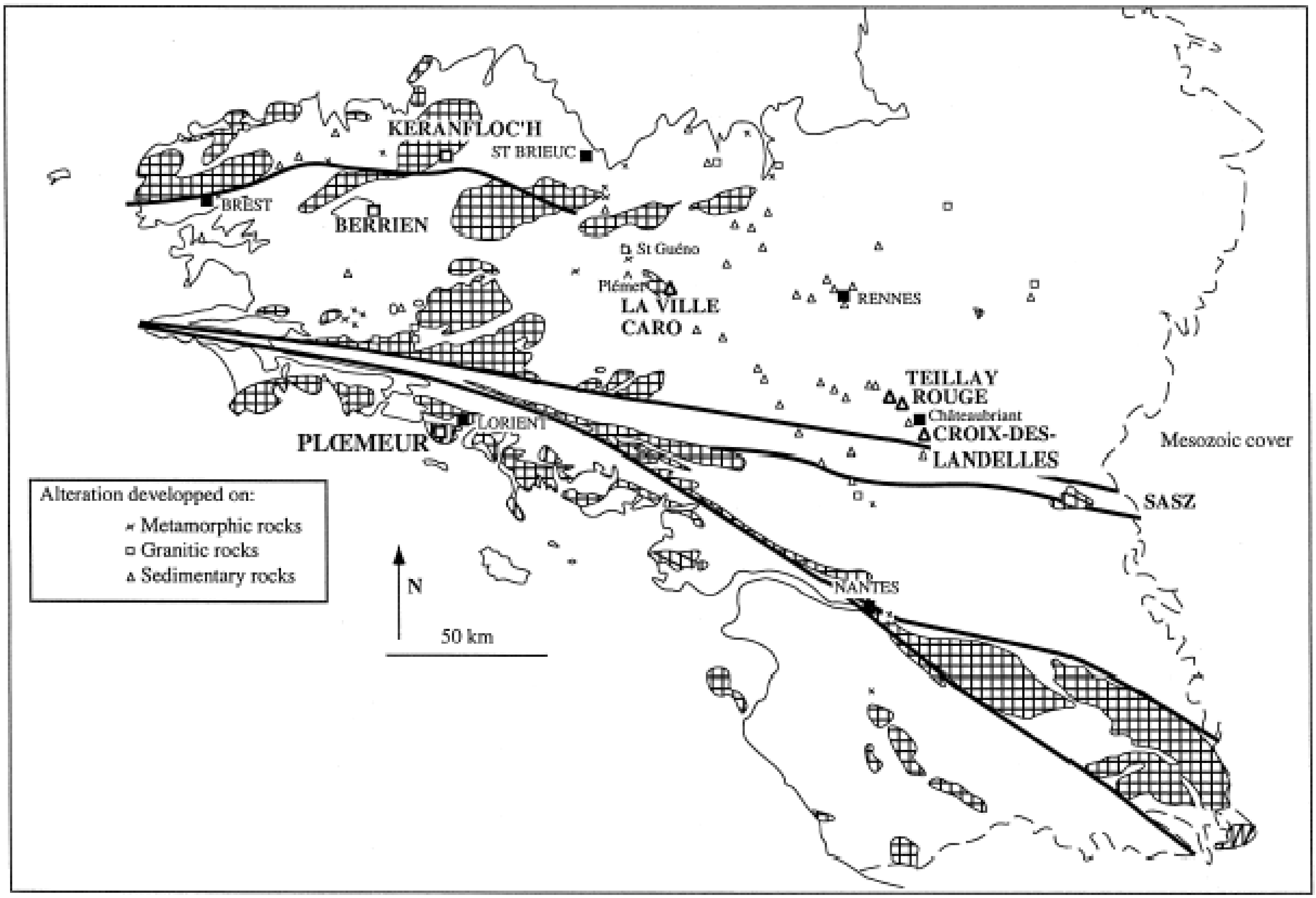
The sonic log can be used to detect overpressured zones in a well. An increase in pore pressures is shown on the sonic log by a drop in sonic velocity or an increase in sonic travel time



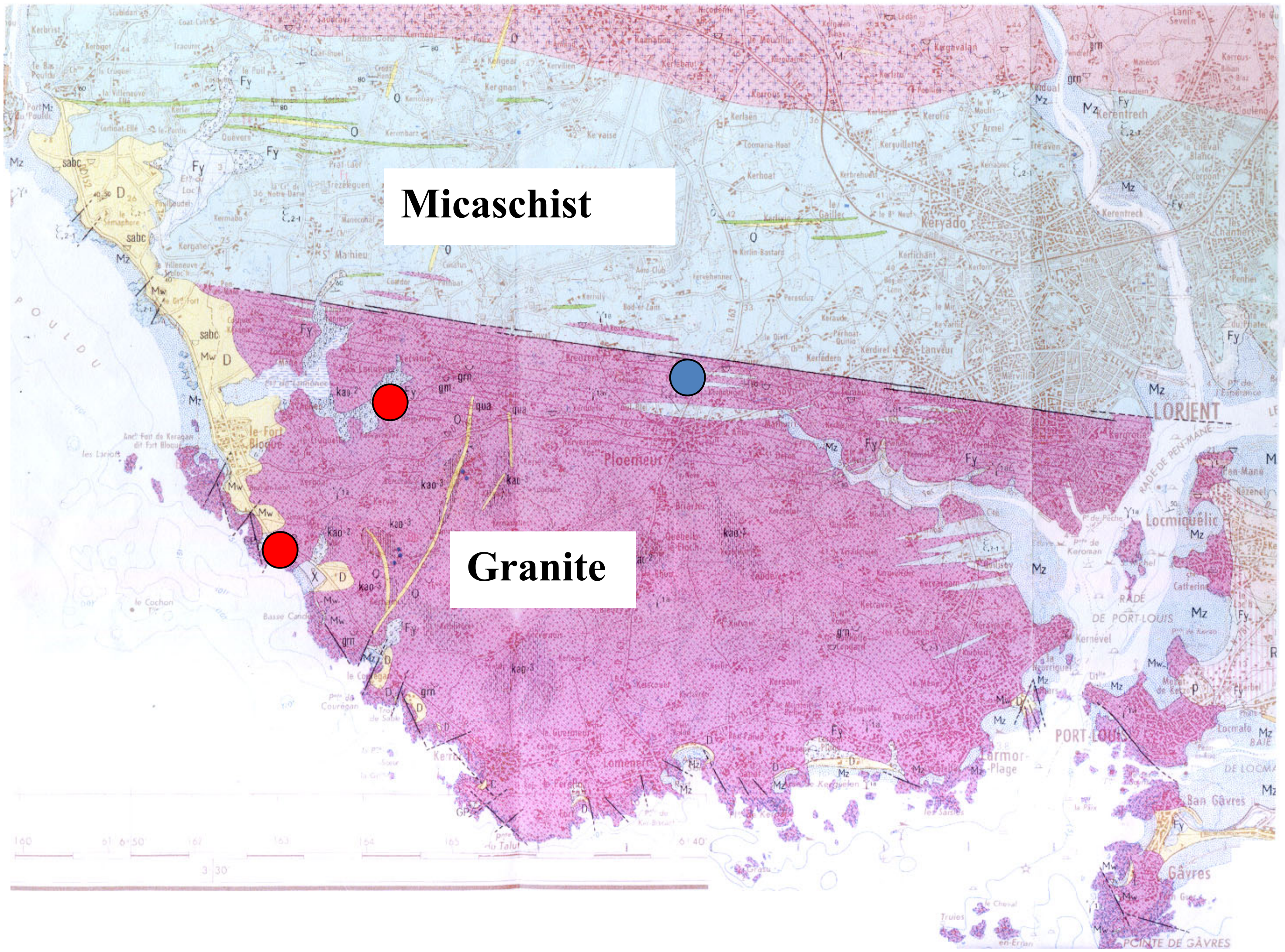
III. **Sonic method**

➢ Example

- Ploemeur (Bretagne) : hydrogeological reservoir



III. Sonic method



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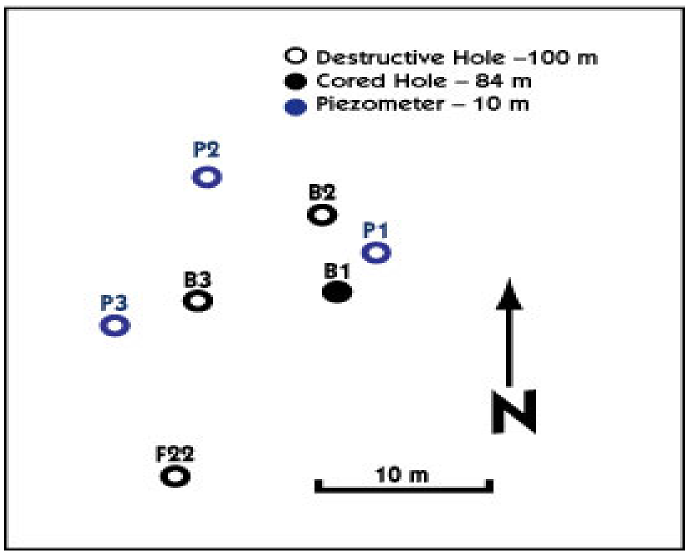

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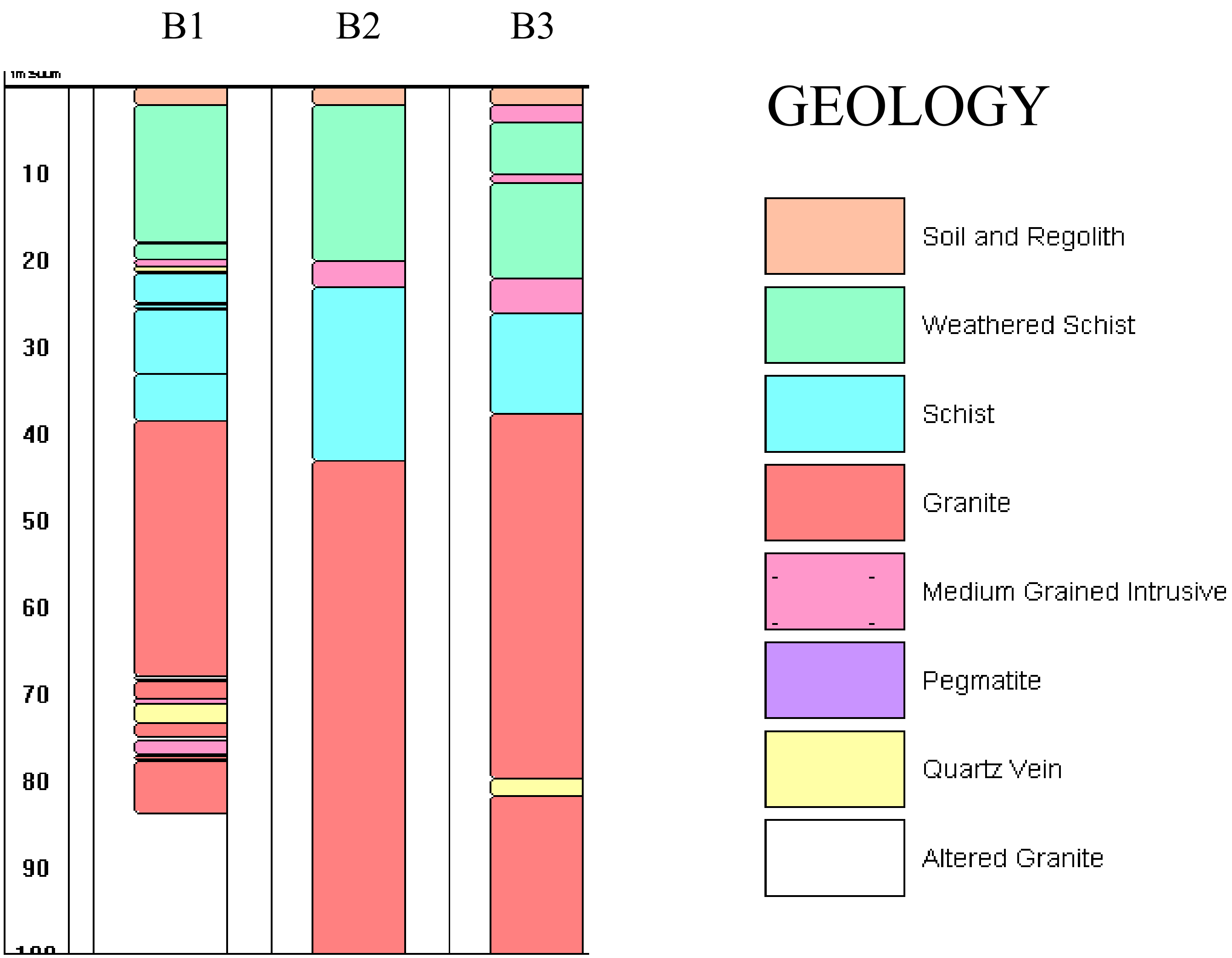
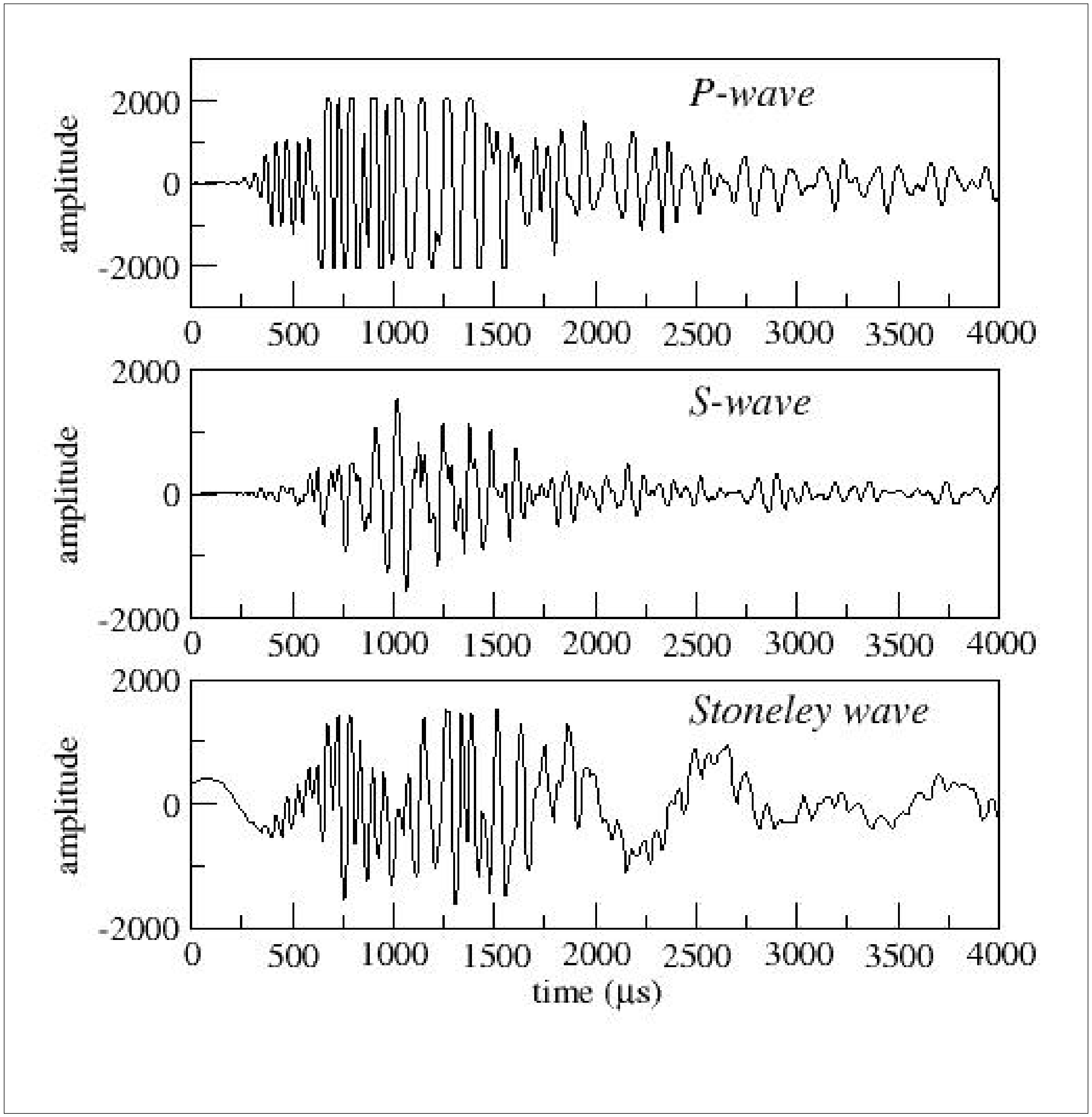
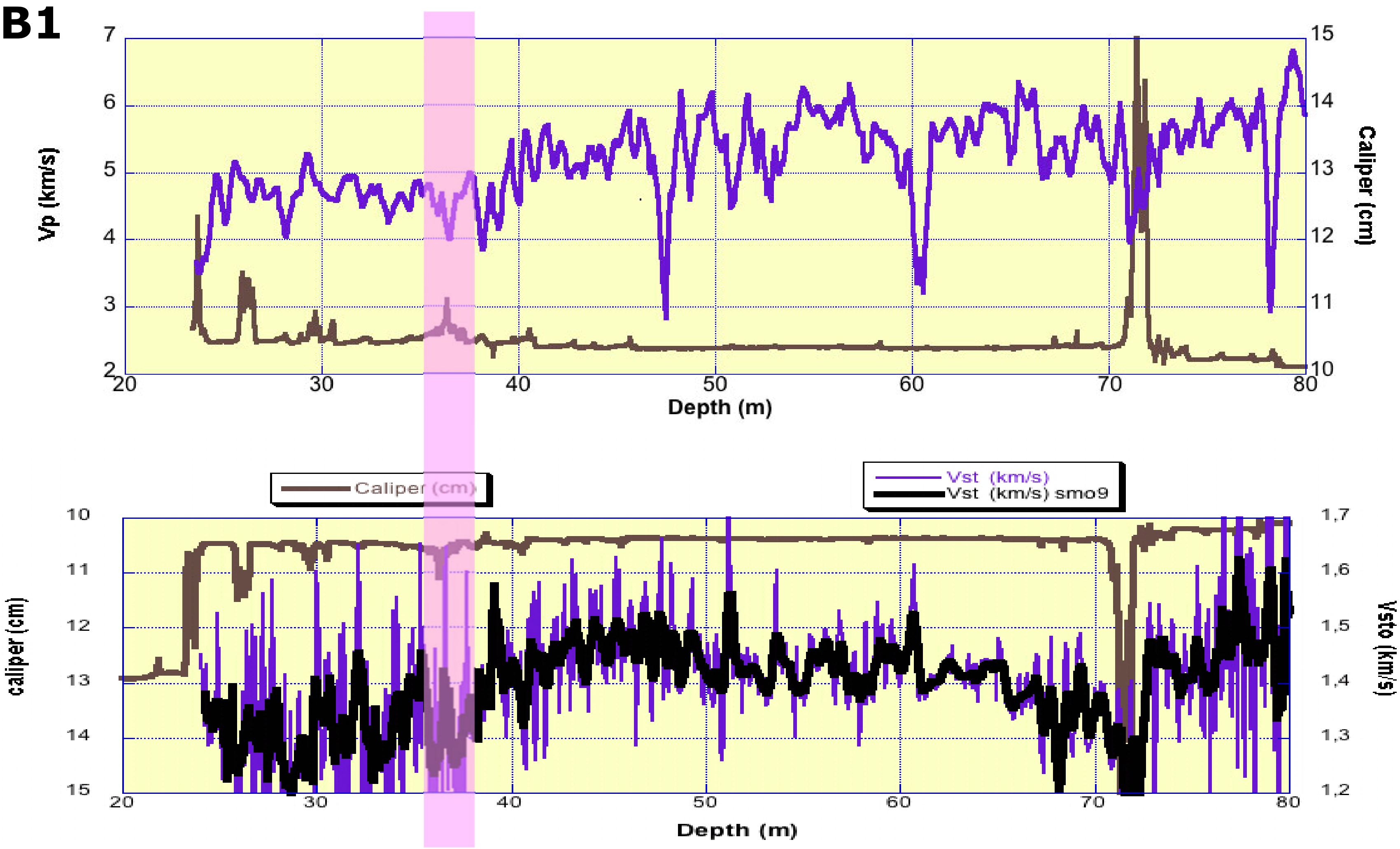


III. Sonic method

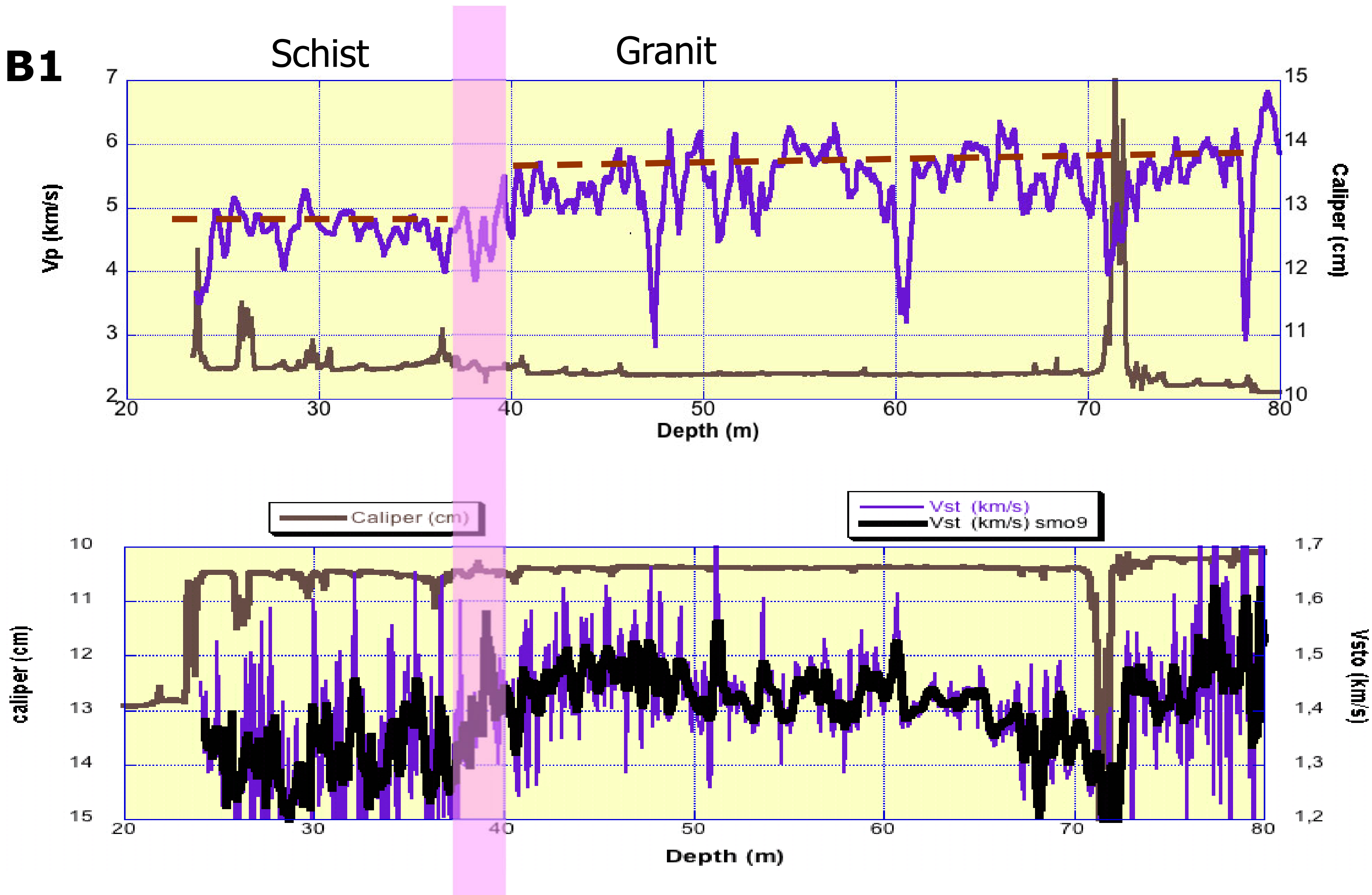


III. Sonic method

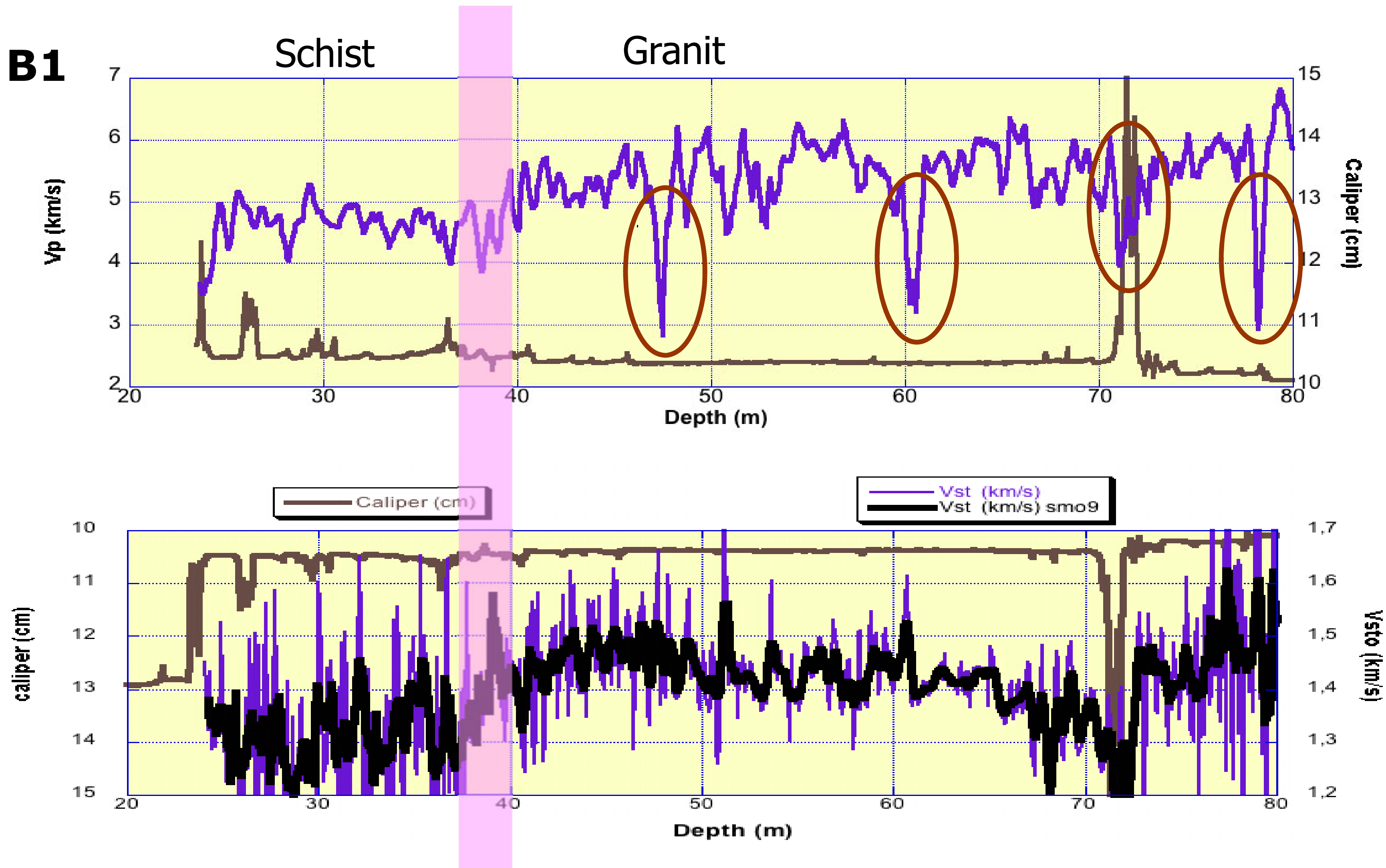
B1



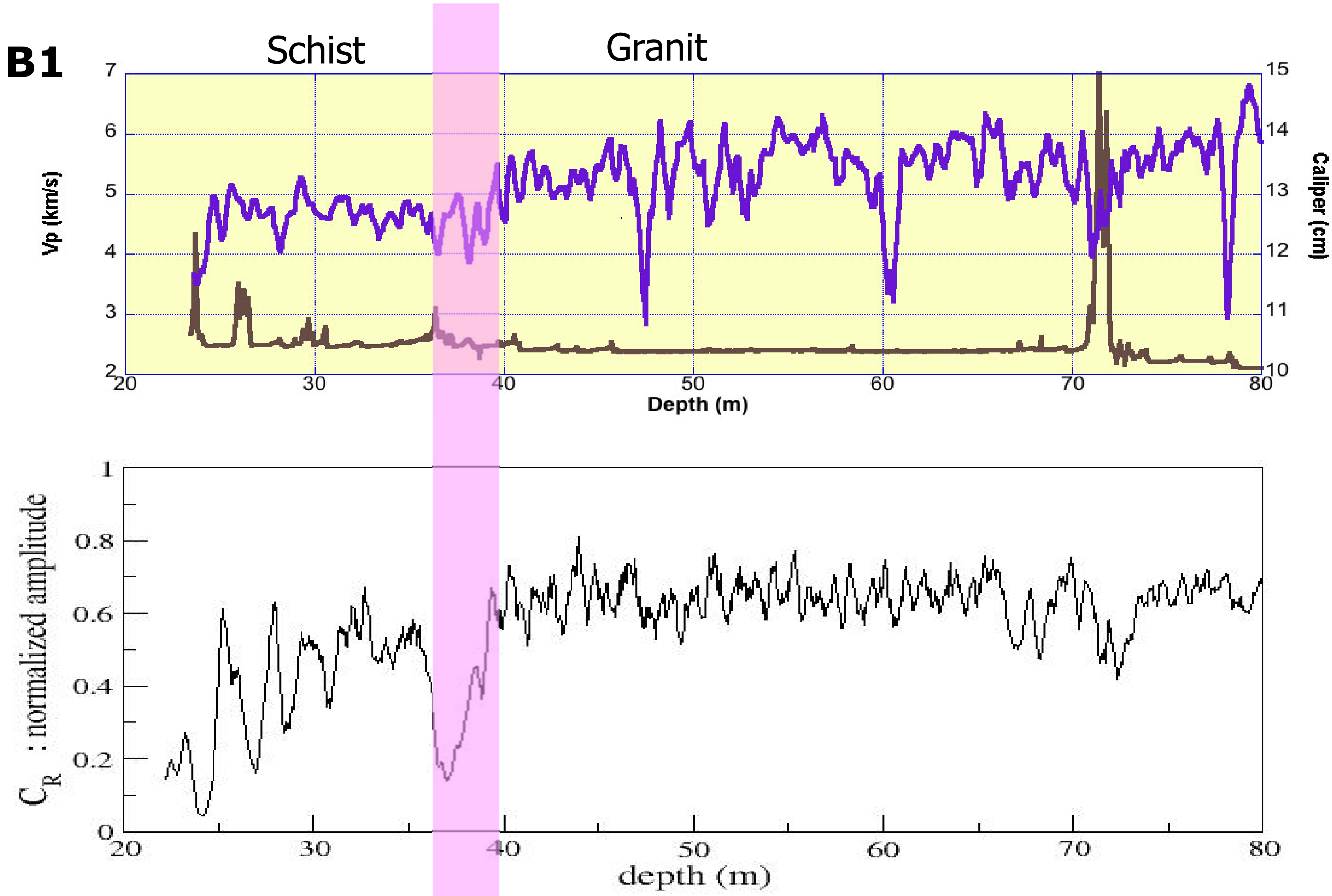
III. Sonic method



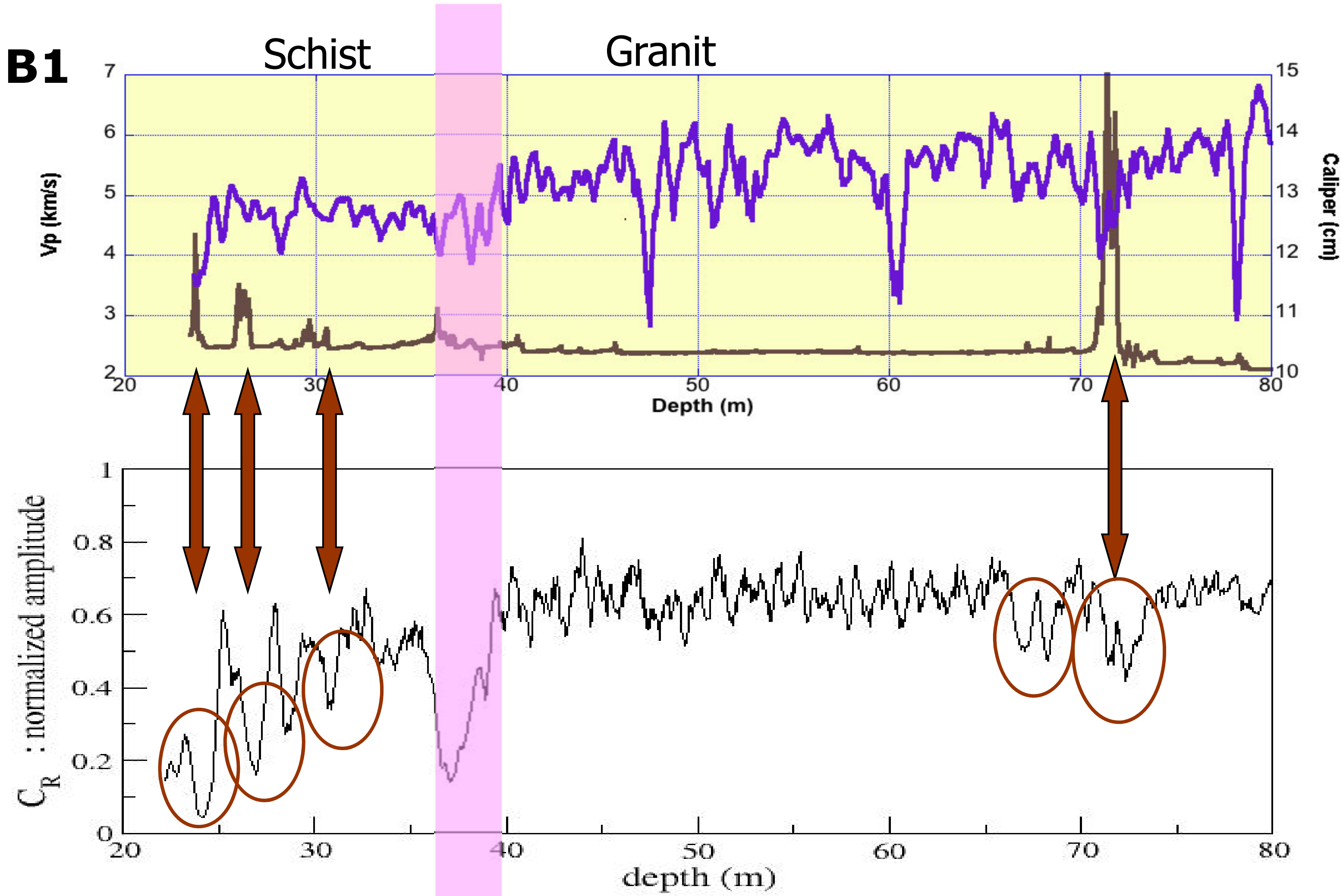
III. Sonic method



III. Sonic method

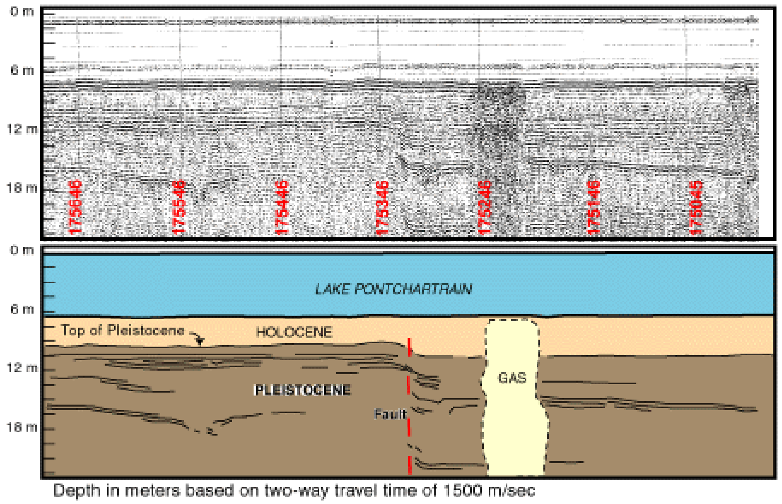


III. **Sonic method**

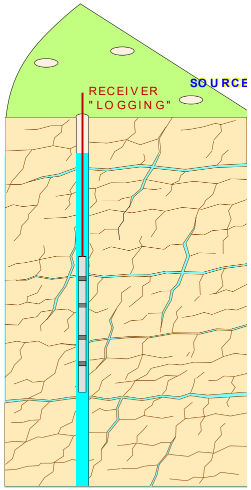


IV. **Seismic prospecting in wells**

Subsurface geophysics

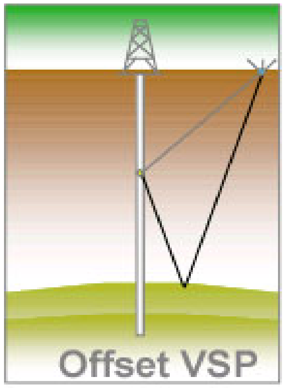


calibration



Borehole geophysics

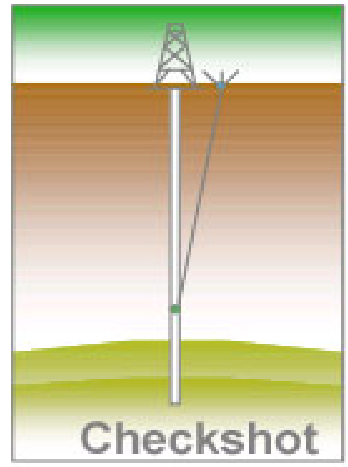
Seismic prospecting in wells

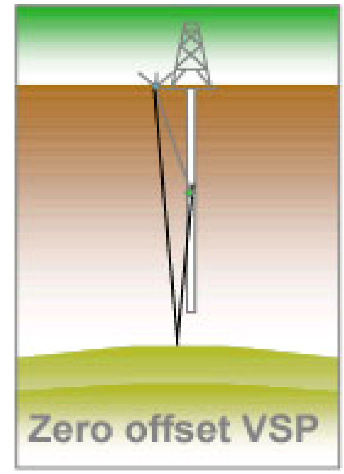


IV. **Seismic prospecting in wells**

Emitter in surface

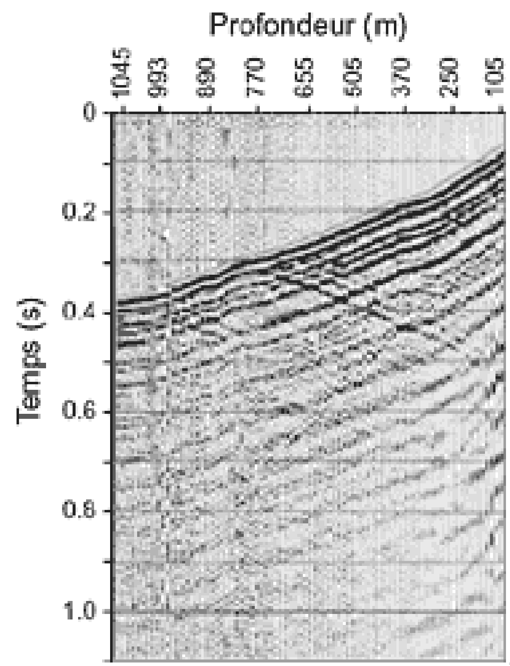
Receptor in the borehole





Resolution = dm to m

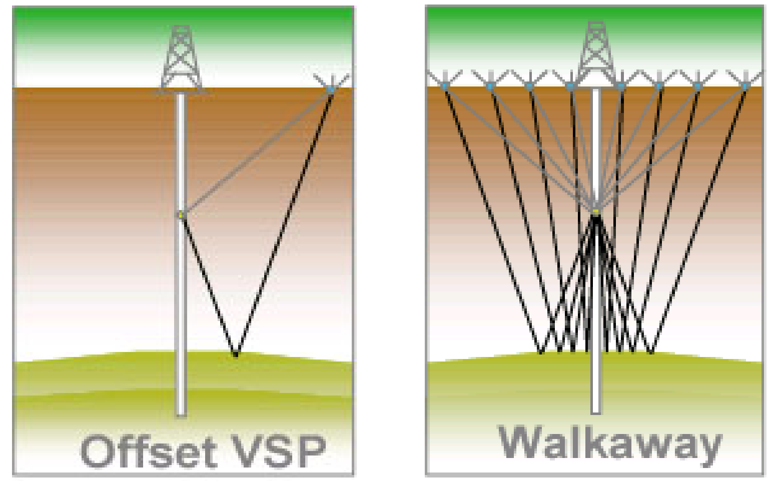
Lateral Investigation = 10m to 100m vertical

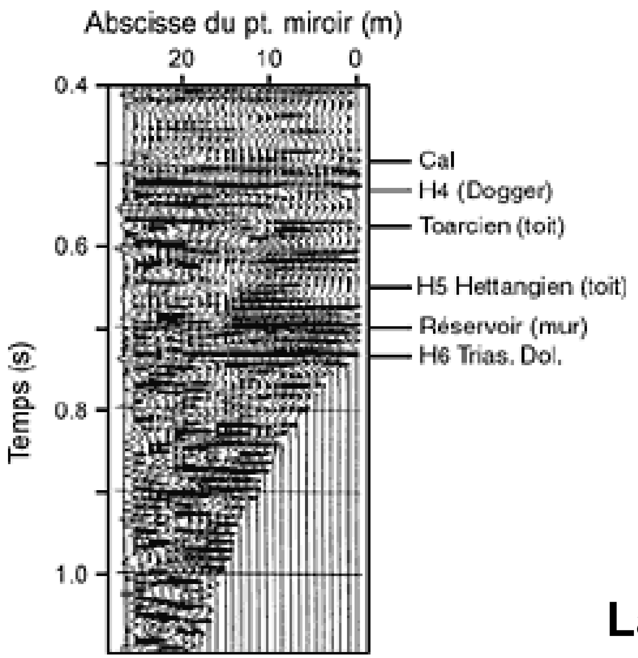


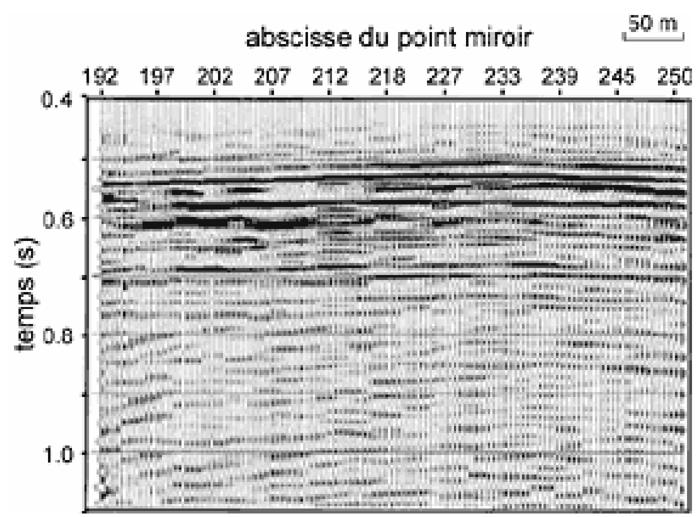
IV. **Seismic prospecting in wells**

Emitter in surface

Receptor in the borehole





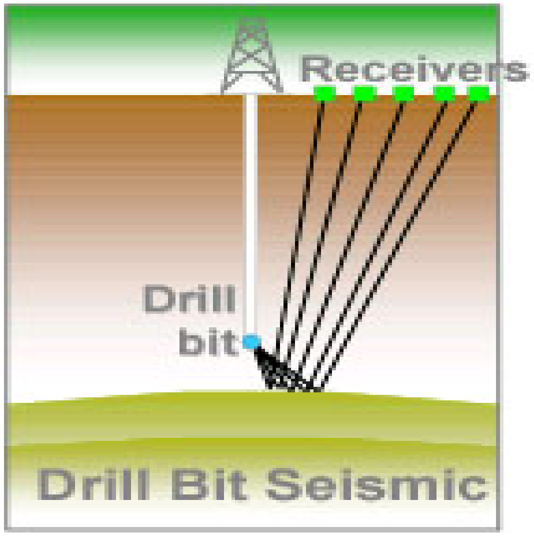


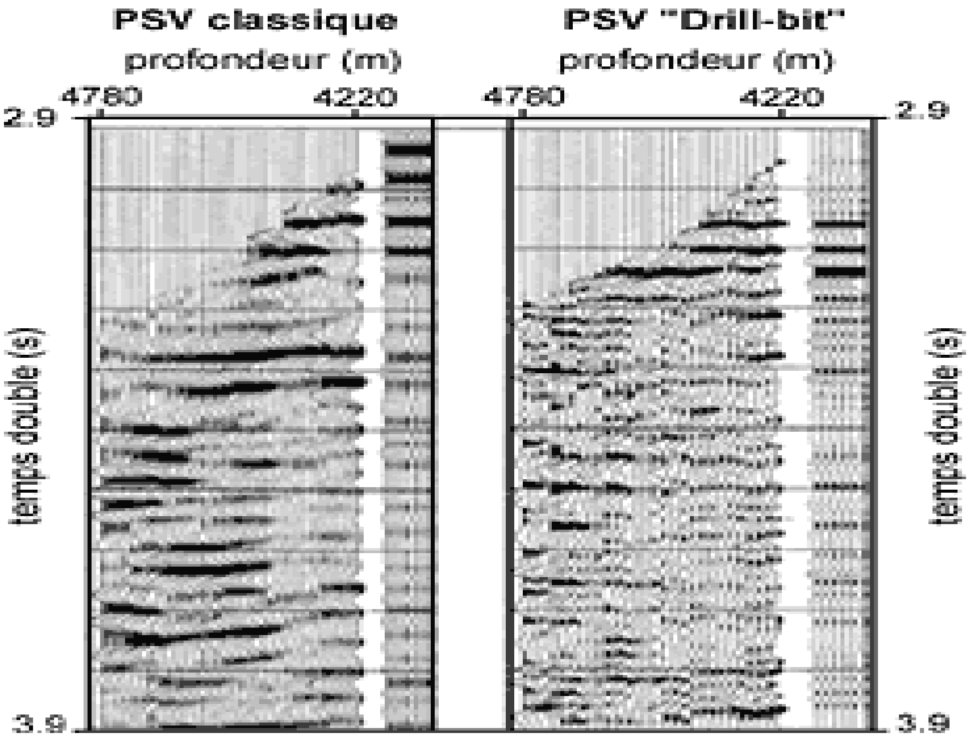
Lateral investigation (100 m to km)

IV. **Seismic prospecting in wells**

Emitter in borehole

Receptor in surface



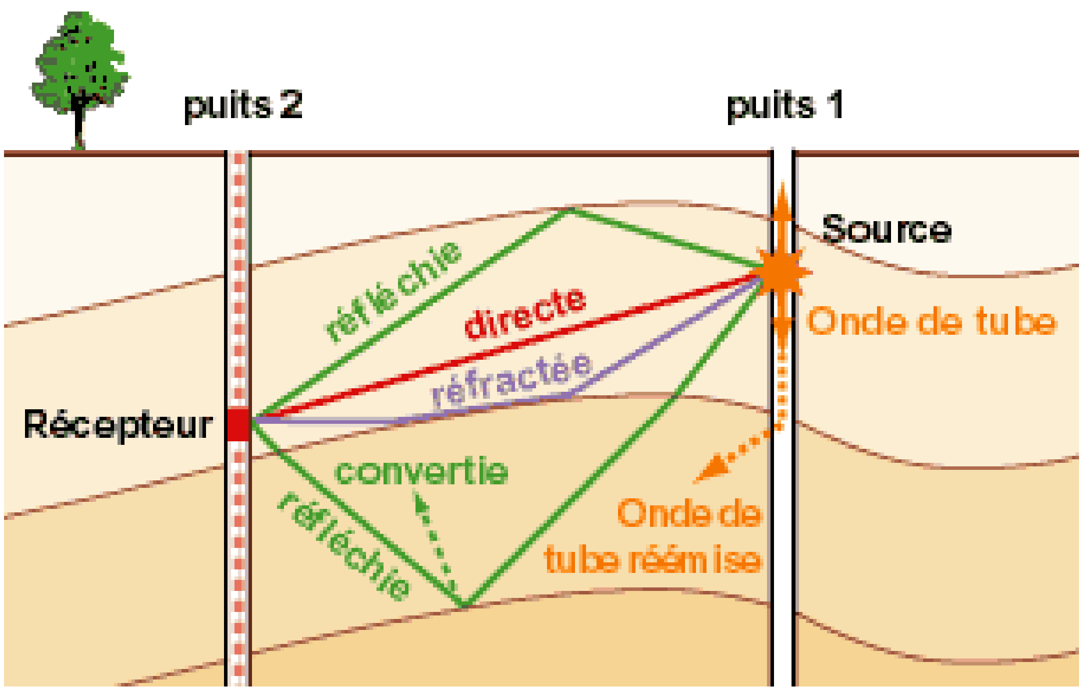


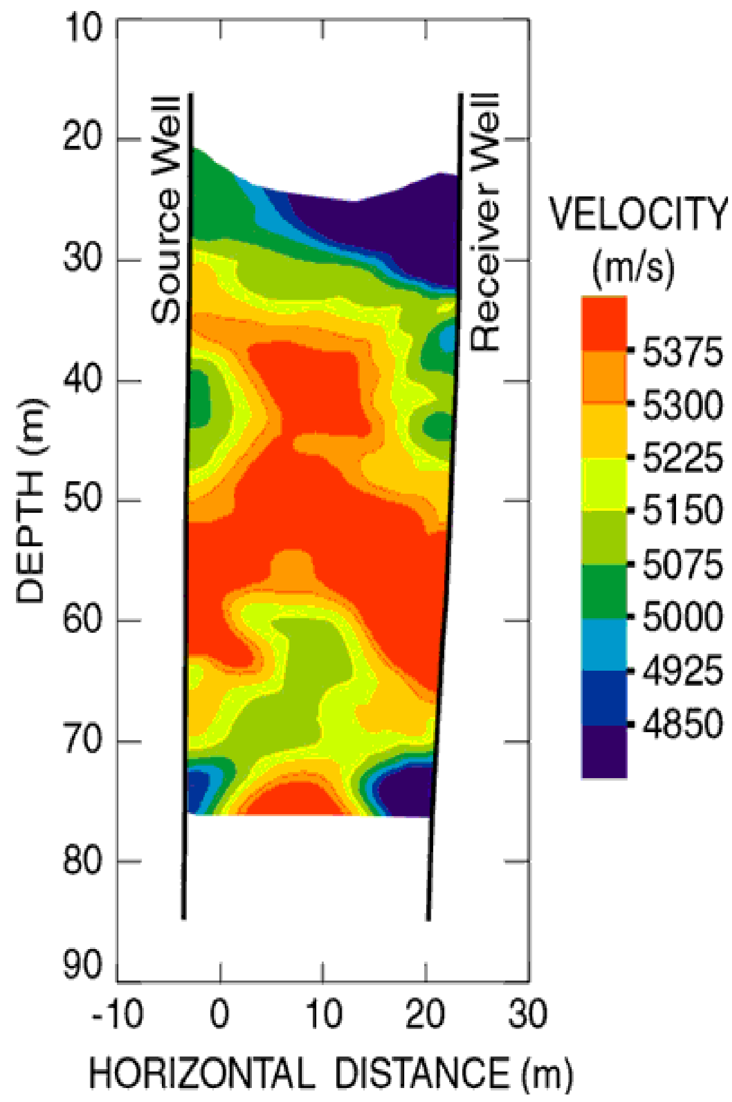
IV. **Seismic prospecting in wells**

- Tomography

Emitter in borehole

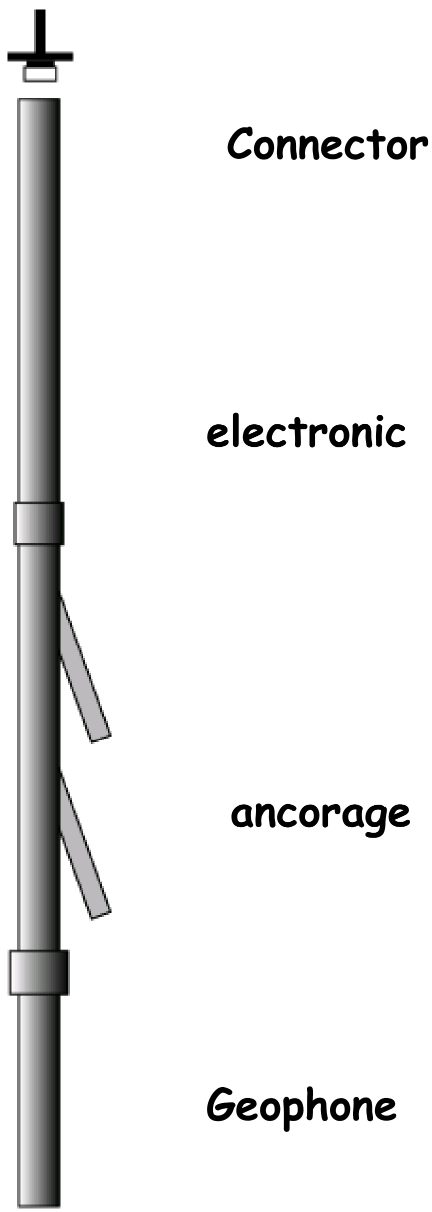
Receptor in borehole





IV. **<u>Seismic prospecting in wells</u>**

- Tools



IV. Seismic prospecting in wells