3

Acoustic logging

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3.1 Introduction

For many years, the transmission of an acoustic wave through media has been used for borehole measurements. Acoustic logging is an approach to measure the sound propagation velocity in geological formations, using a device composed of a transmitter and a receiver system. Originally, this measurement method, called sonic logging, was essentially intended to measure the interval (Δt) of arrival times of the first compression wave, with two receivers that are 25 to 50 cm apart, the energy being emitted by a transmitter located about 1 m from the first receiver. A slowness (inverse of velocity) curve is obtained from which is calculated the propagation velocity of the refracted sonic wave (15 to 30 kHz) in the formations. In this case, only the picking of the first arrival of the compression wave (P) in the media traversed is taken into account. The use of so-called sonic logging to determine the

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velocity of compression waves is a common and relatively well-established practice (Summers and Broding, 1952; Vogel, 1952).

Full waveform acoustic logging or acoustic coring is based on the analysis and processing of the various wave trains (refracted waves, guided waves, reflected waves) recorded by the tool.

Full wave field recordings enable the determination of the propagation velocities of the various modes and some petrophysical parameters, and the ascertainment of lithological and mechanical information (Gaudiani, 1982; Arditty, Arens and Staron, 1984; Morris, Little and Letton, 1984; Paillet and Turpening, 1984; Mari, Coppens, Gavin and Wicquart, 1992; Mari, Arens, Chapellier and Gaudiani, 1998; Mari, Gaudiani and Delay, 2011).

The borehole may be an open hole, a cased hole (steel and/or PVC), or a cemented cased hole. In the latter type, acoustic logging is used to monitor the cementation and to determine the characteristic parameters of formations (velocities…).

Acoustic logging has a vertical resolution of a few centimeters, and a lateral one of centimeters for interface modes, decimeters up to a meter for retracted modes, and up to ten meters for reflected modes. It provides detailed information of a borehole as a function of depth, in terms of acoustic wave velocities and rock petrophysical characteristics. The exploitation of the reflected modes can provide an image comparable to a time microseismic section which, in favorable cases, allows the tracking of layer boundaries and an estimation of their dip. Combined with density logging, it provides an acoustic impedance log, which is variable with depth, and is converted to time after correction, calibration and tying.

Figure 3.1 is an example of a full waveform acoustic log. The acoustic tool (left image in figure) is a flexible tool with a small diameter and composed of a transmitter and 2 receivers. The distance between the transmitter and the first receiver is 3 m, the distance between the two receivers is 25 cm. The depth reference is ground level. Recording depth corresponds to the depth of the point located halfway between the two receivers. The right side of the figure shows an example of an acoustic section obtained by using a transmitter-receiver pair, 3 m apart. In this representation, the vertical axis represents the depth at which the sensor is located (3 m in this case), and the horizontal axis represents the listening time (3 ms). The acoustic section is composed of acoustic traces. Each acoustic trace is the acoustic recording measured by the receiver, which is 3 m from the transmitter, over a listening time of 3 ms. Different wave trains can be identified on the recording.

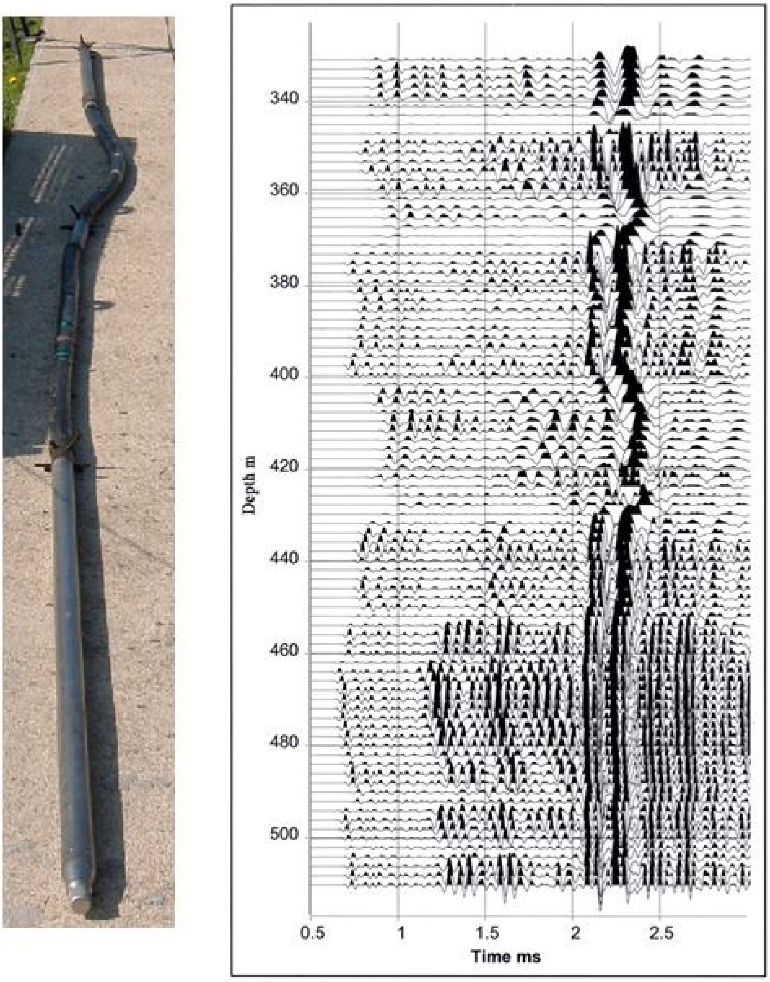


Figure 3.1 *Full waveform acoustic logging – tool and acoustic section.*

3.2 Acoustic logging data acquisition

In this section, we present:

- The necessary resources for data acquisition.
- Implementation in the field.

3.2.1 *Necessary resources for data acquisition*

Listed below are the necessary resources in terms of equipment, vehicles and personnel.

- **Equipment:**
  1. logging unit, which includes: a number of probes, a winch with several hundred meters of cable, to which the probes are connected, a recording and digitization unit (digitization can be done at the sensor level), a system for the visualization and printing of the field recordings, and a depth measurement system.
  2. one or more acoustic probes
  3. a seismic source (weight drop), if a VSP operation is planned with the acoustic logging
  4. a lifting system with pulleys to lower the logging (and VSP) probes
  5. equipment should be checked periodically (maintenance, calibration).
- **Vehicles:**
  1. either: a logging unit (preferably all-terrain/off road), enabling the transport of personnel and equipment (logging probes and optional VSP probes...)
  2. or: a logging unit and one vehicle or a trailer to transport the VSP source (if a VSP operation is planned with the acoustic logging).
- **Personnel and expertise:**
  1. two suitably qualified operators to execute the procedure (winch, lowering of logging probes, acquisition);
  2. one geophysicist (Head of Mission) qualified for data quality control at acquisition and can also be an operator.

3.2.2 *Implementation in the field*

In this section, we describe:

3.2.2.1 Description of an acoustic logging operation in a vertical borehole

In vertical boreholes, it is assumed that there is a cylindrical symmetry of the geological formation with respect to the borehole axis. For this measurement, the hole must be in water (borehole mud). The acoustic probe is lowered using centralizers. It is recommended to first measure the borehole diameters (caliper).

After setting the zero (probe reference) according to a reference plane (raft, rotary table...) or on the ground surface, the probe is lowered to a given depth chosen by the operator to make stationary measurements. These measurements enable the verification of the acoustic recordings, the correct operation of the tool, the repeatability of measurements, and the assessment of the signal-to-noise ratio and the adjustment of certain acquisition parameters (gains...). The tool is then lowered to the bottom of the borehole. A control acquisition can be made during the descent (downlog), to ensure that there will be no saturation at acquisition. The measurement operation is then carried out during the ascent (uplog), at constant velocity, according to the sampling interval in depth. A typical ascent speed is 4 to 6 m/min.

3.2.2.2 Acoustic probes

Either monopole or dipole tools are used. Monopole tools are the most commonly used. Transmitters and receivers are multidirectional (Figure 3.2a). In the fluid, transmitters generate a compression wave, which creates in the formation a compression wave (P-wave) and a shear wave (S-wave) at the refraction limit angles. Dipole acoustic tools are used to access the S parameters of slow formations and are equipped with polarized transmitters and receivers. Such tools generate polarized compression waves perpendicular to the borehole axis. These compression waves create flexure modes at the well wall that generate pseudo-shear waves in the formation that propagate parallel to the well axis (Figure 3.2b).

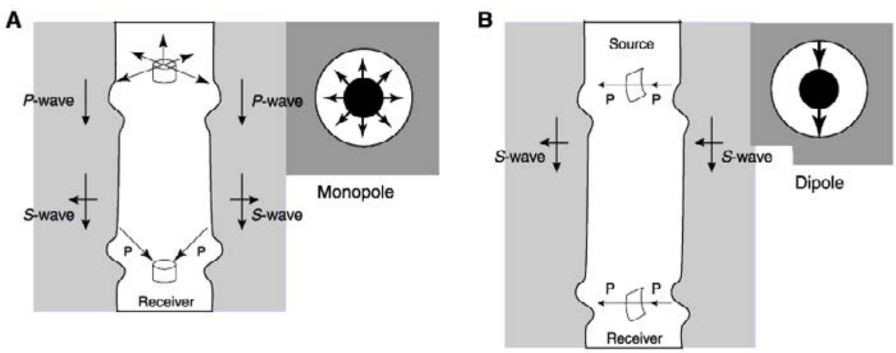


Figure 3.2 *Types of Sonic Array transmitters a) Monopole transmitter emitting a multidirectional pulse. b) Dipole transmitter emitting a directed pulse (modified from Zemanek et al., 1991).*

When the shear velocity of the formation is lower than the P velocity of the borehole fluid, the flexural wave travels at the S-wave velocity and is therefore the most reliable logging method for estimating a shear velocity log. The difficulty, however, is that these tools from the oil industry are rigid and long (about 10 m long and 10 cm in diameter). Their implementation is not suitable for geotechnical boreholes. Although an adaptation is available for the geotechnical field, namely PS suspension logging (PSSL), which involves a flexible tool. The PSSL method was originally developed in the mid-1970s by researchers at Japan's Oyo Corporation (Kaneko et al., 1990) with geophones used as receivers. Today, the companies

Robertson Geologing and Geovista have also developed a probe with hydrophones. The gap between the sources and receivers is 2 to 3 m and the frequency is in the range of 100 to 1,000 Hz. The source is a horizontal electromagnet that produces a pressure wave in the borehole fluid (electrodynamic source). At the borehole wall, this pressure wave is converted into P and S seismic waves that travel radially away from the wall of the hole. These waves are reconverted into pressure waves in the borehole fluid and detected by the receivers (vertical component for the P-wave; horizontal component for the S-wave).

An acoustic tool is characterized by:

- the type of system:
  - monopole: transmission frequency 10-40 kHz
  - dipole: transmission frequency 1-3 kHz
- transmitter and receiver type:
  - magnetostrictive
  - piezoelectric
- number of transmitters and receivers:
  - standard, with one or two transmitters and two receivers
  - receiving antenna with four to eight receivers
- distance between receivers: from ten to fifty centimeters
- transmitter offset relative to the first receiver: from one to five meters
- mechanical characteristics:
  - rigid framework
  - flexible framework
- time sampling interval:
  - 5 or 10 µs for a monopole tool;
  - 20 µs for a dipole tool
- listening time:
  - 2 or 5 ms for refracted mode analysis;
  - 10 ms or more for reflected mode analysis

Figure 3.1 left shows a monopole acoustic tool, that is flexible and has a small diameter (50 mm), which is used for geotechnical borehole studies but also for acoustic measurements in the oil sector. The transmitter is magnetostrictive (transmission frequencies: 17-22 kHz). It can be equipped with two pairs of receivers (both near receivers (1 - 1.25 m) and far receivers (3 - 3.25 m)). The acoustic examples presented in Chapter 5 were obtained using this tool, developed by P. Gaudiani.

Figure 3.3 shows examples of acoustic tools.

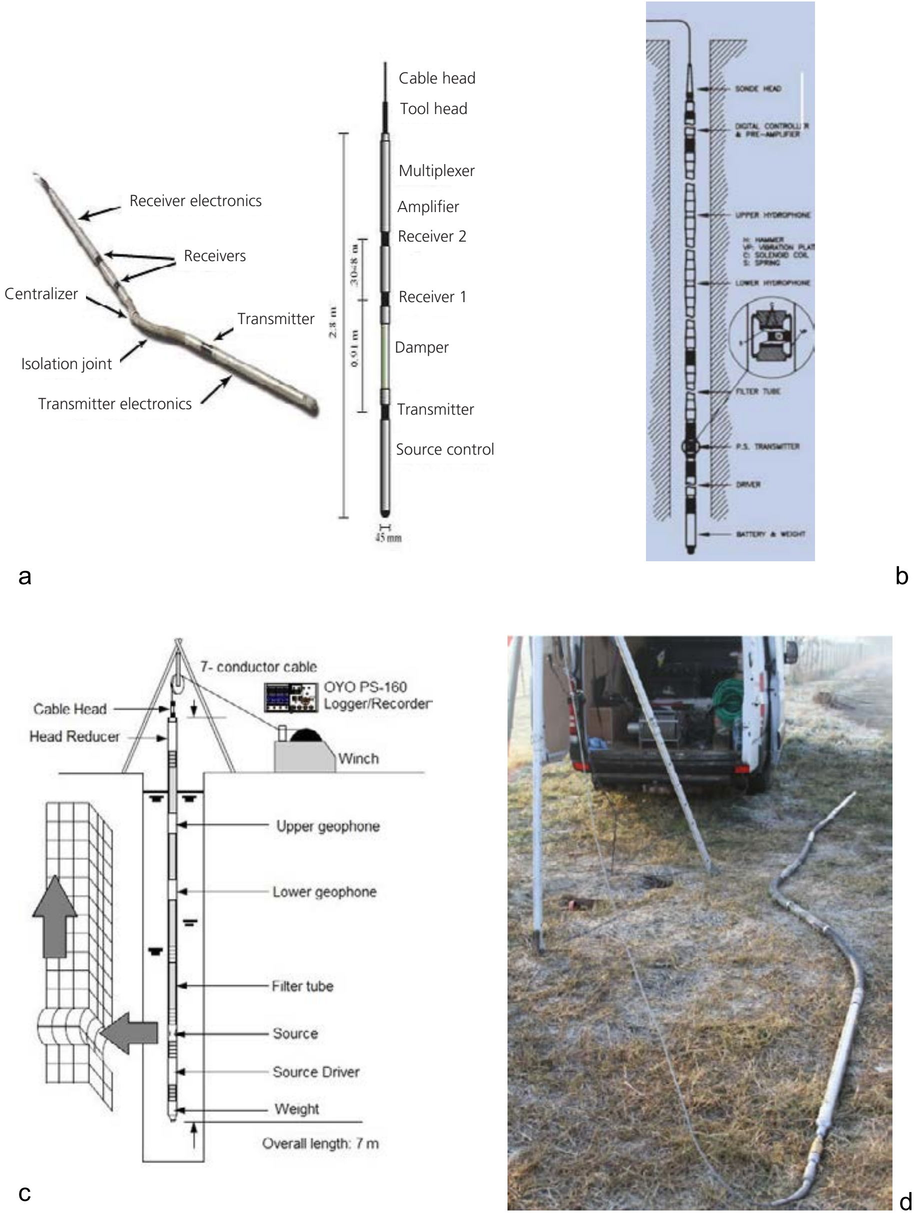


Figure 3.3 *Acoustic tools. a) monopole tool (Mount Sopris); b) dipole tool (Robertson). c) and d) PSSL (OYO) principle and view of the tool (GeoVision-EDF document).*

3.2.2.3 Acquisition and visualization parameters

The acoustic recording can be visualized in the form of constant offset acoustic sections, the offset being the distance between the transmitter and a receiver. Each constant offset section is a two-dimensional record (time: vertical axis; depth or length: horizontal axis, or vice versa). The sampling interval in depth must be chosen to avoid the spatial aliasing phenomenon on the constant offset sections for subsequent processing of the acoustic data.

In practice, the sampling interval in depth is chosen to be equal to a fraction of the distance separating the tool's two receivers, which enables the refracted arrivals to simulate direct-inverse shots and to make compensated velocity measurements.

Acquisition gains must be chosen to avoid saturation, especially for guided modes. However, if acquisition is done to obtain a P-wave velocity log, one can choose gains to amplify the compression waves so as to facilitate the picking of the first arrival times (threshold), even if it means saturating the guided modes and having to make a second "run" to acquire guided modes in preserved amplitude.

3.2.2.4 Acoustic logging in deviated well

If the well is deviated, the reflected waves at the boundaries of the layers crossed by the borehole are recorded by the acoustic tool. These waves can be exploited and processed to provide detailed micro-seismic analysis in the vicinity of the well.

3.2.2.5 Security

Site security must be ensured by the Head of Mission, in accordance with the Quality System of the service provider. Access to the measurement area must be secured.

3.2.2.6 Quality control

During the ascent of the acoustic probe, the operator controls the quality of the recordings on the various receivers of the acoustic probe, particularly the noise level. It may be beneficial to reduce the speed of ascent in noisy areas, but the sampling interval in depth must remain constant.

3.2.2.7 Production

For an acoustic log, the average logging speed is between 4 and 6 m/min. This type of logging is rarely performed on its own. It is typically part of a set of measurements obtained over several "runs".

3.3 Acoustic waves

In a vertical well, monopole tools can enable the recording of five propagation modes:

- refracted compression wave;
- refracted shear wave, only in fast formations ($V_S > V_P$ fluid);
- fluid wave;
- two dispersive guided modes, which are pseudo-Rayleigh waves and Stoneley waves:
  - Pseudo-Rayleigh waves are reflected conical dispersive waves (Biot, 1952) with phase and group velocities which, at low frequencies (<5 kHz), approach the S velocities of the formation, while at high frequencies (>25 kHz) they asymptotically approach the propagation velocity of the compression wave in the fluid. These waves exist only in fast formations.
  - Stoneley waves are dispersive interface waves. In fast formations, they have phase and group velocities that approach the fluid velocity at high frequencies asymptotically, and from a lower value. In slow formations, they are more dispersive and sensitive to the S-wave parameters of the formation. At low frequencies, Stoneley waves are analogous to tube waves observed in downhole (Chapter 1) and VSP (Chapter 2).

Full waveform acoustic measurements are represented as constant offset sections or common transmitter or receiver point gathers, similar to those used in seismic surveys. An constant offset section or acoustic coring is a set of acoustic recordings represented as a function of depth, obtained with a fixed transmitter-receiver distance.

Presented below is a set of common transmitter point gathers and a set of constant offset sections showing the different wave types that can be observed on these recordings. The common transmitter point gathers are synthetic seismograms that have been made using the modeling programs of Jacques Quiblier (1997). These programs enable the modeling of acoustic data in slow and fast formations. The formation is infinite, elastic and isotropic. It is defined by the propagation velocities of P-waves (V_P) and S-waves (V_S), by the density ρ, and two quality factors (Q_P, Q_S) that are characteristic of the attenuation. The well of constant diameter (16.1 cm) is filled with water (Vf = 1,500 m/s, ρf = 1g/cm^3) and is of infinite length. The tool of infinite length has the acoustic properties of the fluid. It consists of a transmitter (monopole or dipole) and nine receivers (measuring points). The distance between the transmitter and the first receiver is 1 m. The distance between 2 consecutive receivers is 12.5 cm. The time sampling interval is 10 µs, the listening time 4 ms. At each measurement point, the algorithm calculates the three components of the displacement (Ur, Uθ, Uz: radial, tangential and vertical displacements) and the pressure P. In our simulations, the characteristics of the formations are:

– for the slow formation (V_S < well fluid velocity):
  V_P = 2,760 m/s

V_S = 1,380 m/s

ρ = 2.3 g/cm^3

$Q_P = Q_S$ = 90

– for the fast formation (V_S > well fluid velocity):

V_P = 4,000 m/s

V_S = 2,000 m/s

ρ = 2.3 g/cm^3

$Q_P = Q_S$ = 90

Figure 3.4 a shows the common transmitter point gather obtained with a monopole tool in a slow formation. Without amplification, the only visible wave is the Stoneley wave. With an amplification of 60 dB, the refracted P-wave clearly appears. The measurement of its dip enables the determination of the V_P velocity of the medium.

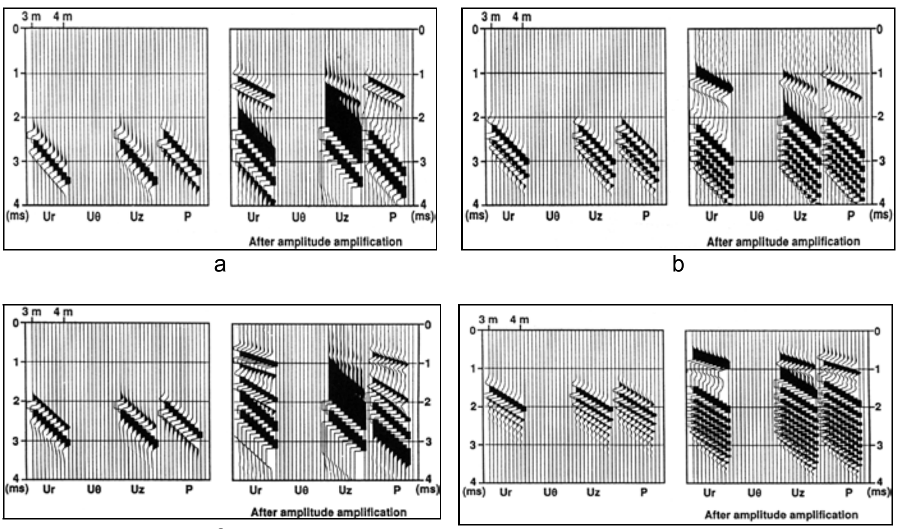


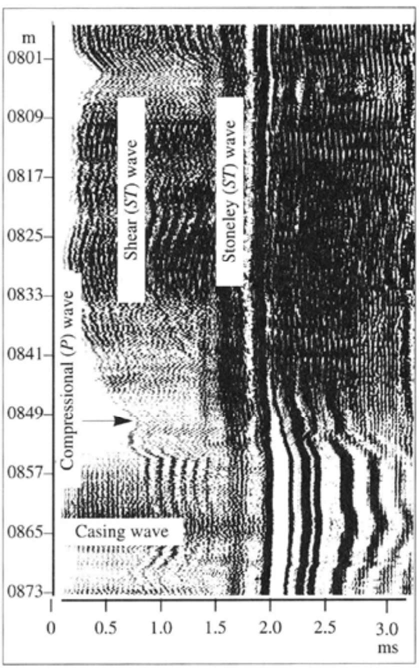
Figure 3.4 *Acoustic logging in slow and fast formations. a): monopole tool in slow formation, b): dipole tool in slow formation, c): monopole tool in fast formation, d): dipole tool in fast formation.*

Figure 3.4 b shows the common transmitter point gather obtained with a dipole tool in a slow formation. Without amplification, only the flexural mode is visible between 2 and 3.5 ms. After amplification, the refracted P-wave appears between 1 and 1.5 ms. The flexural mode gives a very good estimate of the V_S velocity of the formation.

Figure 3.4 c shows the common transmitter point gather obtained with a monopole tool in a fast formation. After amplification, the refracted P-wave appears in the 0.5 - 1 ms range, the refracted S-wave in the 1.5 - 2 ms range, and the Stoneley wave, which is clearly visible without amplification, in the 2 - 3.5 ms range.

Figure 3.4 d shows the common transmitter point gather obtained with a dipole tool in a fast formation. The highly energetic flexural mode is present in the 1.5 - 2 ms range, and the refracted P mode is present in the 0.5 - 1 ms range after amplification.

Figure 3.5 a is an example of a 3 m constant offset section, that therefore corresponds to measurements on a receiver that is 3 m away from the transmitter, where these propagations are clearly visible. The source is a magnetostrictive monopole transmitter. The presence of the refracted S-wave indicates that the formation is fast. When there is an impedance contrast between two formations with a dip similar to that of the plane perpendicular to the hole axis, these different waves (refractions and interface waves) can convert and reflect as shown in Figure 3.5b and reveal on the constant offset sections a number of chevron patterns at slow apparent velocity. Such reflections can also occur at casing connections, cavities and any other well wall heterogeneities.



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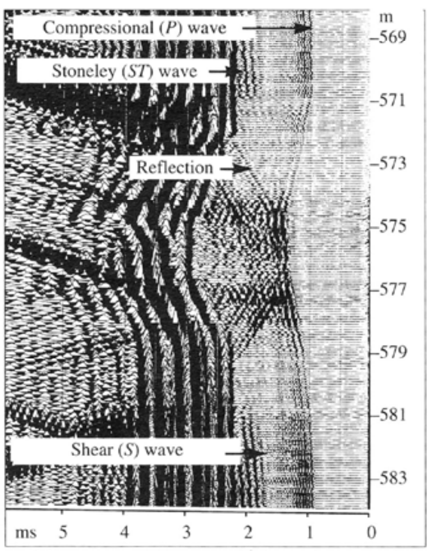


b

Figure 3.5 *Acoustic sections (SEMM document). a): example of an constant offset section obtained with a monopole source. We observe the refracted P arrival, the refracted S arrival, the Stoneley wave and casing waves. b): Example of refracted-reflected P-waves and reflected Stoneley waves at impedance contrasts in the well. On an constant offset section, these arrivals are in the characteristic form of chevron patterns at slow apparent velocity.*

3.4 Processing sequence

Conventional processing of an acoustic log enables time-depth relationship and velocity logs to be obtained at the well, as well as certain mechanical parameters such as the Poisson's ratio.

The processing sequence includes:

1. Editing (elimination of poor quality recordings).
2. Calculation of acoustic velocities by picking the arrival times of the different wave trains or by velocities scanning and semblance processing.
3. Quality control of velocities (measurement of the correlation coefficient) and of pickings (for example, by flattening the wave train by applying static corrections equal to the picked times).

Comments:

- If the picking algorithm uses a threshold, the detection of erroneous picks (spikes and cycle jumps) must be done when editing the velocity logs. This technique is only applicable to compression waves.
- If the velocities are measured by semblance, it is recommended to use a tool with a large offset between the transmitter and the first receiver (about 2 to 3 m) and with at least 4 receivers. Measurement is facilitated if the wave trains are well separated in time.

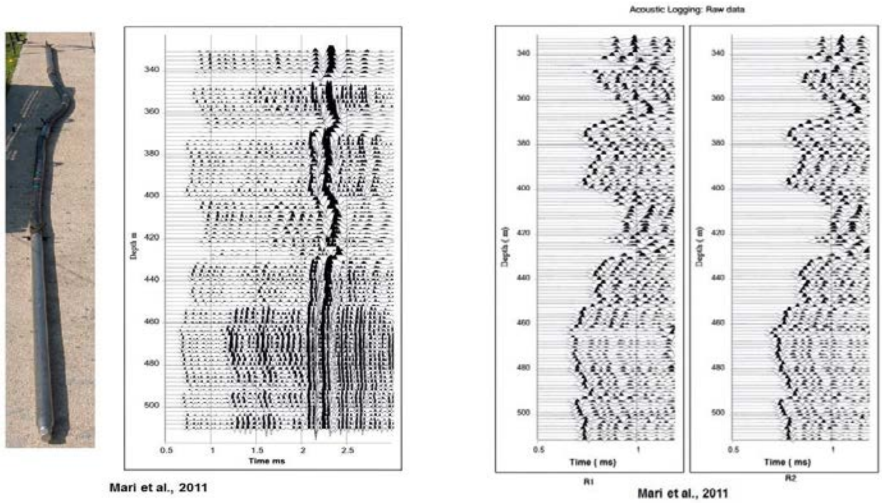
Optional:

1. Measurement of the amplitudes of the different wave trains and calculation of the amplitude and attenuation logs.
2. Measurement of the frequencies of the different wave trains and calculation of the frequency logs (attenuation, resolution...)
3. Calculation of the acoustic porosity (Wyllie's formula)
4. Calculation of synthetic films. It is recommended that tying (block shift and minimum Δt methods) of Δt acoustic measurements on VSP measurements is carried out.
5. Calculation of elastic modules (geomechanical: choice of models used)
6. "Seismic reflection" type processing of reflected waves and obtaining micro-seismic sections in the vicinity of the well (deviated or horizontal wells)

Processing takes from one to several days (or even weeks: micro-seismic processing is equivalent to seismic reflection processing), depending on the processing options required. If the required processing is only the P velocity log, picked by threshold, it can be obtained in real time in the field.

Examples of conventional acoustic data processing are presented below.

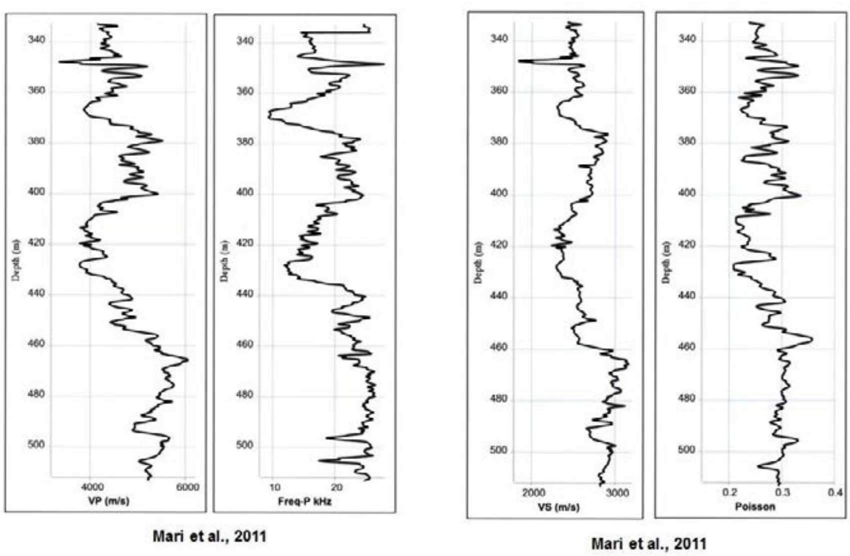
The first example (Mari et al., 2011, Figure 3.6) is an example of acoustic data acquired in a fast formation (formation V_S > well fluid V_P).



a

b

Figure 3.6 a and b *Example of acoustic data recording.*



c

d

Figure 3.6 c and d *Example of acoustic data processing - velocity measurement. a): Tool and 3 m constant offset acoustic section. b): Acoustic recordings on 2 receivers, 25 cm apart. c): Compression and frequency velocity logs, d): Shear velocity and Poisson's ratio logs.*

On the 3 m constant offset acoustic section (Figure 3.6a), we can see the first arrival refracted P-wave, the refracted S-wave and the associated Rayleigh waves in the 1-2 ms time interval, the latter being particularly visible for depths greater than 440 m. Figure 3.6b shows the two 3 and 3.25 m constant offset acoustic sections, in the 0.5-1.1 ms time interval, centered on the refracted P-wave. The Stoneley acoustic waves are visible after 2 ms. It can be noted that the latter have a higher frequency content at depths greater than 440 m. The processing consisted of calculating the V_P and V_S velocity log, the Poisson's ratio log, and the refracted P-wave frequency log, using the instantaneous frequency. The different logs are presented in Figure 3.6c and d.

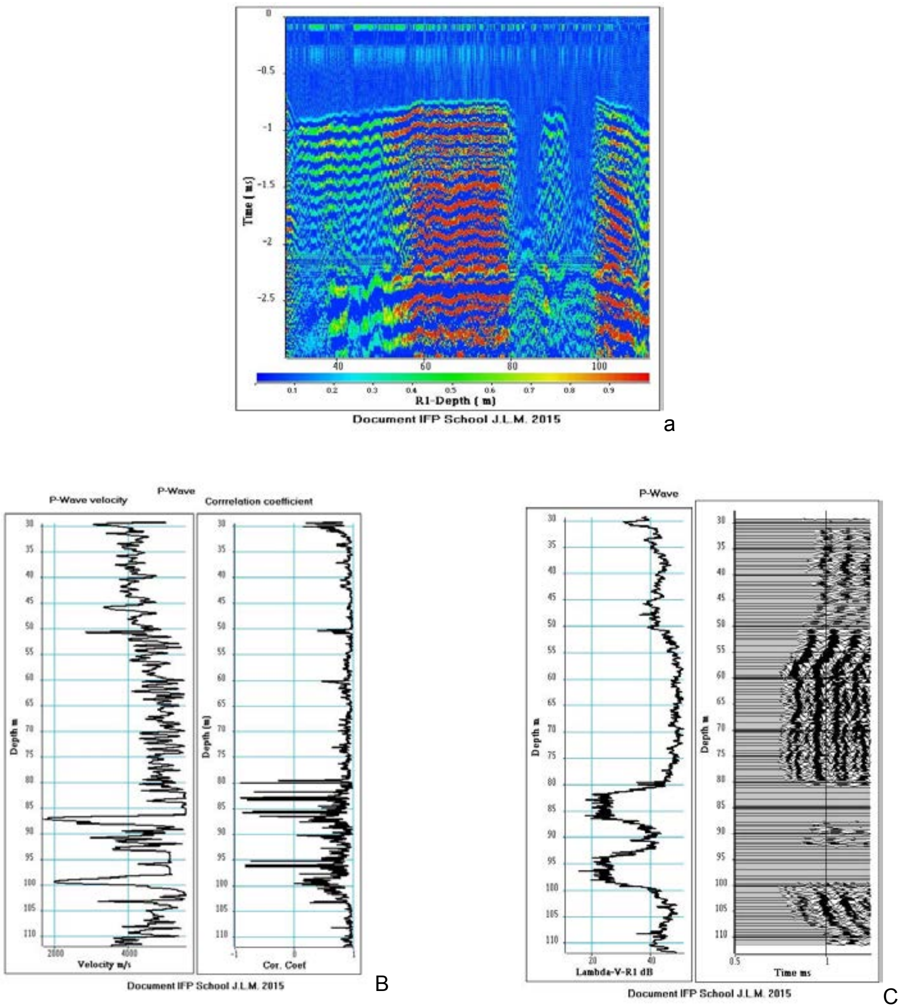


Figure 3.7 *Example of acoustic data processing. a): 3m constant offset acoustic section b): Velocity log (waves) and correlation log. Low values of velocity and correlation coefficient indicate the presence of karstic levels. c): P-waves amplitude log. The very small amplitudes indicate the presence of karstic levels.*

The acoustic data of the second example (Mari and Porel, 2015) were acquired in a carbonate formation. The results are presented in Figure 3.7. Figure 3.7a shows the 3 m constant offset acoustic section, we can see the refracted P-wave, the refracted S-wave and the associated Rayleigh waves, the very high frequency fluid wave at infinite apparent velocity, occurring just before the Stoneley wave. In the depth range of 80-100 m, the presence of two areas with strongly attenuated waves can be noted. Figure 3.7b shows the velocity log of the refracted P-wave and the associated correlation log used for the quality control of the velocity measurement. In the low velocity and high attenuation zones, this coefficient is low. Figure 3.7c shows the amplitude log of the P-wave, obtained by singular value decomposition (SVD) method, in the same depth interval. At this interval, we note a low formation velocity, a strong attenuation, and a low correlation coefficient which all indicate the presence of karstic levels. These data are part of the case study presented in Chapter 5.

3.5 Acoustic imaging

In this section, we provide a simple description of the processes of refraction and reflection imaging.

3.5.1 *Refraction acoustic imaging*

The total transit time $T_{i,j}$ between a transmitter i and a receiver j of a refracted wave is equal to the sum of the delays in line with the transmitting point (D_i) and the receiving point (D_j) and the associated transit time to the refractor ($X_{i,j}/V$ with $X_{i,j}$ being the distance between the transmitter i and the receiver j, and V being the refractor velocity):

$$T_{i,j} = \frac{X_{i,j}}{V} + D_i + D_j$$

with,

$$\frac{X_{i,j}}{V} = \sum_{k=i}^{j-1} dt_{k,k+1}$$

The quantity $dt_{k,k+1}$ is the propagation time in the formation between two successive positions of depth k and k+1. Figure 3.8 shows the path of the refracted wave between a source S at position i and a receiver R at position j. The delays D are simple functions of mud parameters (thickness and velocity hm and Vm) and the parameters of the well's weathering zone (thickness and velocity ha and Va). The delay in S is equal to the travel time between S and B minus the travel time between A and B. The calculation of the delay at each recording depth enables the estimation of the extension of the well's weathering zone. This parameter is rarely measured.

If the velocity of the well's weathering zone is greater than the formation velocity (Va > V), the measurement of slowness by the acoustic method does not lead to an estimation of formation velocity, but that of the well's weathering zone.

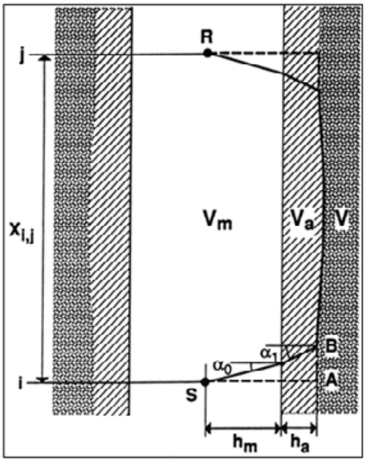


Figure 3.8 *Diagram of the first refracted arrival path (from Coppens and Mari, 1995).*

The average slowness of wave propagation over a given depth interval corresponds to the delay acquired by the wave over this interval. For the same depth position of the transmitter (or reciprocally, the receiver), the delay can be measured by measuring the difference in the arrival time of the wave over each receiver position (or reciprocally, transmitter) located in the depth interval. As a consequence, the slowness of a formation can be estimated by measuring the wave delay by using sorted sonic records, either in common-source point depth gathers or in common-receiver point depth gathers. The average of the two delays then forms a slowness compensated for well effects.

Slowness measurement methods based on the picking of first arrival times for each trace provide logs with a resolution equal to the distance separating two receivers (between half a foot and two feet). The most well known method is the minimum energy threshold picking method. If the threshold is poorly selected, or if attenuation or noise problems modify the energy levels, phase jumps of one or more periods (so-called cycle jumps) may occur, distorting the time measurements.

Using full waveform tools, it is possible to control the pick quality and avoid phase jumps. Picking by threshold can then be advantageously replaced by picking techniques that take into account other criteria for tracking a wave. Mari and Coppens (1992) have proposed a picking method based on the use of artificial intelligence techniques to track a particular wave from one trace to another, and from one shot point to the other. Wave tracking is done using shape and continuity criteria. The shape of the wave is defined by its amplitude and apparent frequency.

Continuity is expressed by a small variation in shape and by a small time difference of the wave from one depth level to another. The use of such a method ensures a pick that is coherent in time, amplitude and frequency. The tool geometry (number of receivers and distance between receivers) and the acquisition geometry (advancement rate) create a redundancy of information at each measurement depth and lead to an estimation of a dispersion or error value for each parameter.

Figure 3.9 shows eight constant offset sections (9 to 12.5 ft) recorded with a multi-receiver tool. The eight sections are presented on a time window of 1 ms framing the first arrival. The first arrival P picking times were used to calculate the slowness log and its measurement dispersion log (Fig. 3.10a and b).

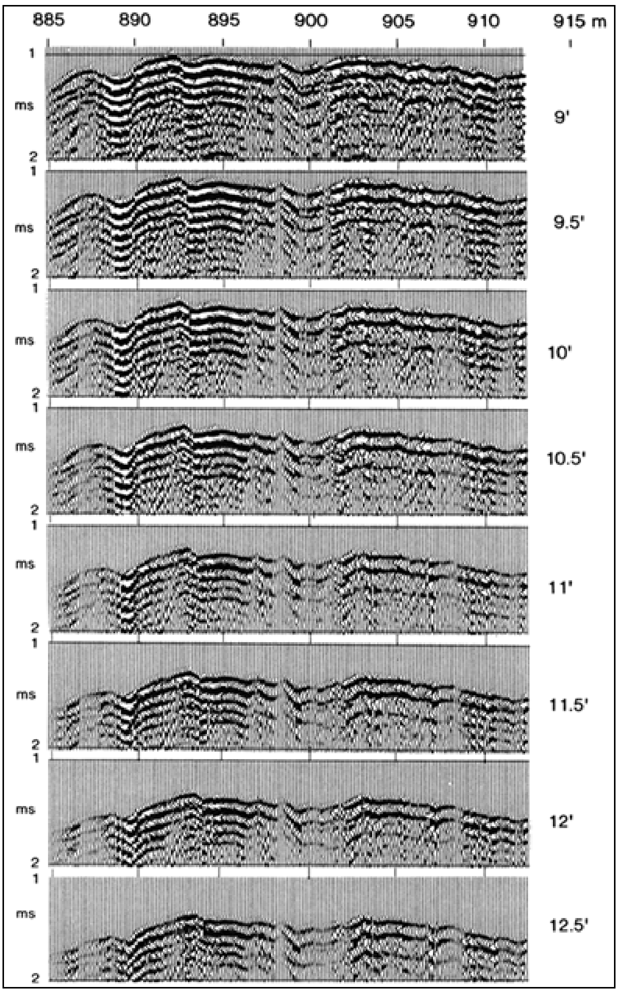


Figure 3.9 *Constant offset sections ranging from 9 to 12.5 feet, recorded with a multi-receiver tool (from Mari et al., 1992).*

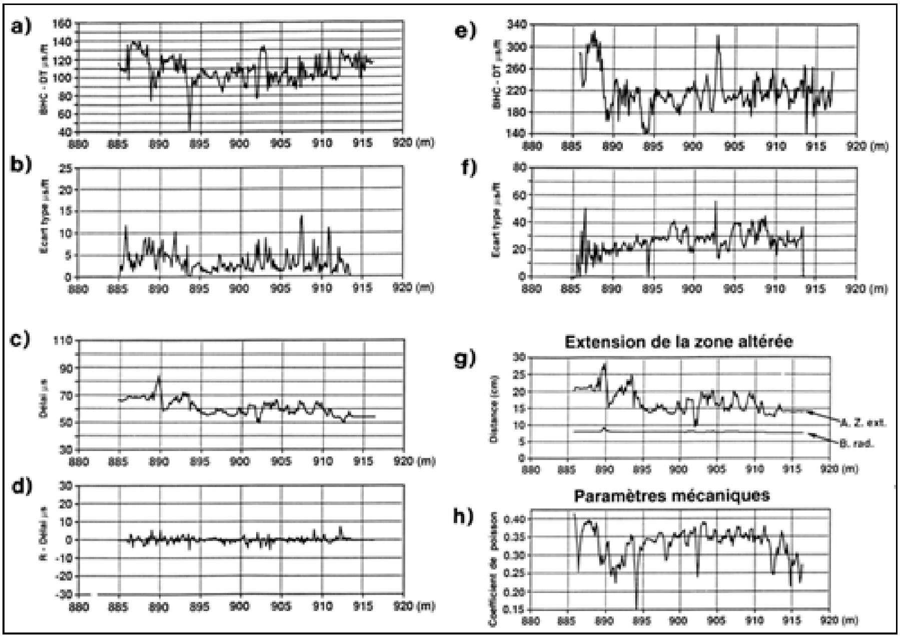


Figure 3.10 *Example of acoustic logs in a sandstone reservoir (from Coppens and Mari, 1995). Monopole tool: (P wave): a) Slowness; (b) Standard deviation of slowness; c) Delay; d) Residual delay. Dipole tool (bending wave # S wave): e) Slowness; (f) Standard deviation of slowness; g) Extension of the weathering zone (P wave); h) Poisson's ratio.*

Knowing the slowness makes it possible to calculate the delays log (Fig. 3.10c). The theoretical arrival times of the refracted wave are then calculated for each shot from the slowness and delay logs. The difference between the calculated times and the actual times represent the measurement dispersion error. This is presented as a residual delay log (Fig. 3.10d) that does not exceed 5 µs, i.e. one half of the time sampling rate in the studied example.

The formation studied being a clay-sandstone slow formation (absence of refracted S modes on the monopole sections), the slowness S of the formation was obtained using the bending modes generated by a dipole-type tool. The measurement of the arrival times of the direct bending wave gives access to the slowness S log and its associated standard deviation log (Fig. 3.10e and f). The combination of slowness logs P and S enable the calculation of Poisson's ratio (Figure 3.10h).

The measurement of the arrival times of the refracted P-wave for each transmitter-receiver pair for the whole of the well gives access to the delay at any measurement point and therefore to an image of the extension of the weathering zone of the well.

Figure 3.10g shows the weathering zone extension log obtained in the clay-sandstone formation. This example shows that the investigation depth of the refracted mode is a few tens of centimeters. In relation to the well wall, the weathering zone locally reaches thicknesses of 20 cm. Increases in the weathering zone in porous zones (890 - 899 m, 911 - 916 m) can be correlated with the presence of weakly consolidated formations. In clay zones (899 - 911 m), weathering zone increases correlate with shaliness.

This example shows that full waveform acoustic logging provides not only formation slowness but also imaging in the well vicinity with decimetric-to-metric scale lateral investigation for refracted modes. We show that the analysis of reflected and refracted modes makes it possible to extend the investigative power of acoustic logging.

3.5.2 *Reflection acoustic imaging*

Processing the reflected modes provides very high resolution acoustic sections (a few tens of centimeters) providing an image with an investigation depth of several meters from the well axis.

In full waveform acoustic logging, the most easily accessible document is the constant offset acoustic section. Figures 3.11 and 3.12 show the results of experimental work carried out in a quarry (Mari, Gavin, Coppens, 1994). Figure 3.11 (top) shows the geological cross section produced from the well information (a vertical well, labeled R1, and a highly deviated well). The deviated well was drilled in the 80 m thick white oolite layer. The abscissa origin is the wellhead of the deviated well. For the ordinates, the geological markers are referenced in terms of depth relative to the quarry top. At the abscissa of the vertical well, the deviated well is 40 m deep. The constant offset acoustic section (Figure 3.11, bottom) shows two types of events: isochronous events with a very high apparent velocity and oblique events. Events with high apparent velocity are refracted arrivals, interface modes (pseudo-Rayleigh and Stoneley waves) and arrivals reflected on acoustic markers parallel to the drain. Oblique events are arrivals reflected on pseudo-vertical fractures or on acoustic markers dipping with respect to the drain. At the 55 m abscissa, the various wave trains are strongly attenuated, indicating the presence of open fractures. Figure 3.12 shows the acoustic section after the filtering of events with a very high apparent velocity. Oblique events, combined with reflections on acoustic reflectors, are clearly visible.

The full waveform recordings provided by the multi-transmitter and multi-receiver tools used for acoustic logging make it possible to carry out a micro-seismic survey of the well, based on the analysis of the reflected or diffracted modes on acoustic impedance discontinuities within formations or at formation boundaries.

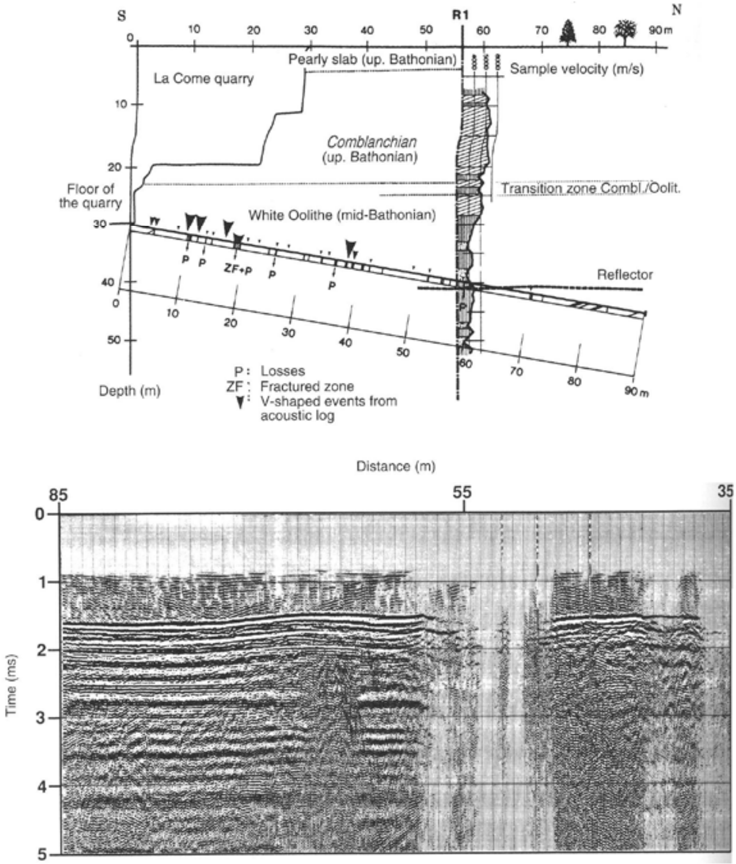


Figure 3.11 *Acoustic imaging in quarry (from Mari et al., 1994). Top: Geological cross section of the Ravières quarry. Bottom: Constant offset acoustic section (3 m), raw data.*

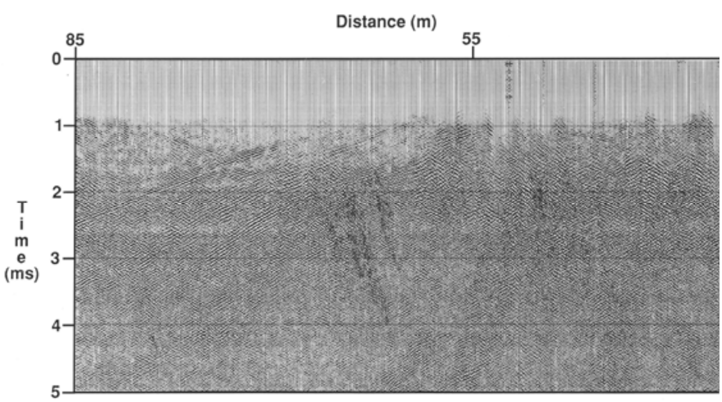


Figure 3.12 *Acoustic imaging in quarry: reflected waves (from Mari et al., 1994).*

Figure 3.13 is an example of acoustic section imaging obtained in a sandstone reservoir intersected by carbonate beds (Fortin et al., 1991). The acoustic imagery clearly shows the distribution of carbonate beds and their dips relative to the well. This acoustic approach to dip estimation requires a thorough multi-coverage processing.

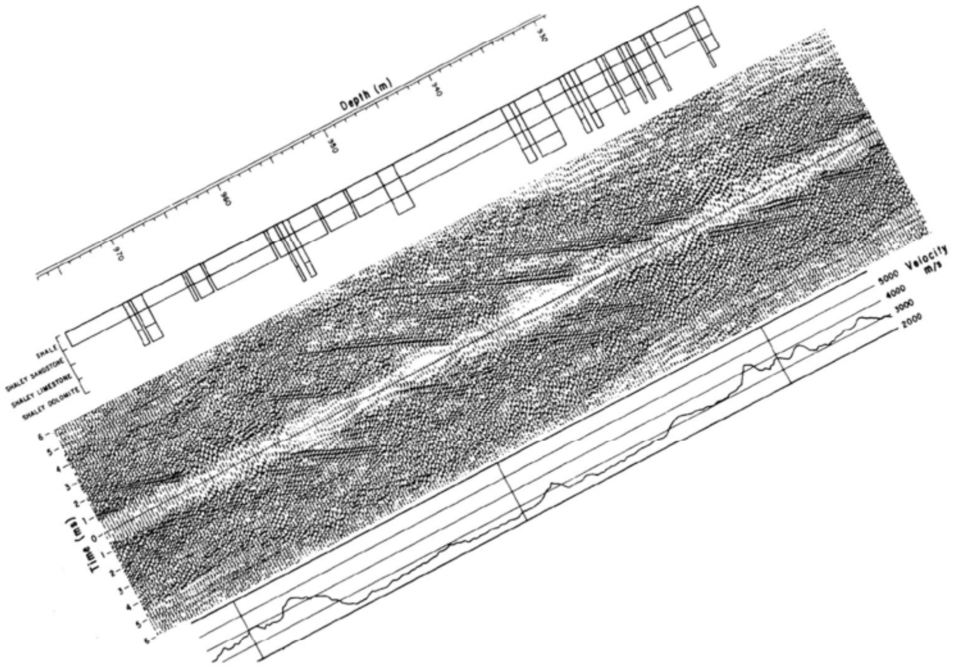


Figure 3.13 *Well imaging using acoustic data: reflected waves EVA tool (SNEAP), multiple coverage processing (CGG) (from Fortin et al., 1991).*

3.6 Characterization of a formation using Stoneley waves

Stoneley waves are used to evaluate the S slowness of slow formations, to study fracturing and to provide an estimation of permeability.

The shear waves can only be generated if the S velocity of the formation is greater than the velocity of the compression wave in the mud; we can then say the formation is fast (as opposed to so-called slow formations). In slow formations, the velocity of S-waves can be indirectly estimated in uncased wells from the Stoneley wave dispersion equation (Biot, 1952; Cheng et al, 1981).

At sonic frequencies (1-20 kHz), it is therefore necessary to independently measure six parameters to derive the S velocity of the formation from the Stoneley mode dispersion equation. These parameters are: the phase velocity of the Stoneley waves at a particular frequency, the fluid density, the formation density, the well diameter, and the velocity of the compression waves in the formation.

The following example is an acoustic logging recorded in a slow formation, consisting of marl in the upper part and limestone in the lower part. The boundary between marl and limestone is at 105 m. The data were acquired with a monopole tool with three receivers spaced 20 cm apart. The offset between the source and the first receiver is 60 cm. Figure 3.14 shows on the left the three constant offset sections recorded with the acoustic tool. On each section we can observe the low amplitude refracted P-wave as a first arrival. The refracted P-wave is followed by a wave of very high amplitude and low frequency, which is the Stoneley wave. The measurement of P-wave and Stoneley wave velocities is carried out by semblance. The semblance panel is shown on the left of the acoustic sections. The vertical axis represents the depth, the horizontal axis is the slowness (inverse of the velocity). The semblance is color coded and expressed as a percentage (high values shown in red). The picking of the maximum semblance (indicated by the continuous black lines) provides for each wave the value of the slowness as a function of the depth. Slowness logs are then converted to velocity logs (Figure 3.14, right). We observe a high correlation coefficient between the 2 velocity logs (0.854). The dominant Stoneley wave frequency is 2 kHz. At these low frequencies, the Stoneley wave dispersion equation can be approximated by a simplified equation proposed by White (1965). White's equation is as follows:

$$\frac{1}{V_{st}^2} - \frac{1}{V_f^2} = \frac{\rho_f}{\rho} \cdot \frac{1}{V_s^2}$$

where V_{st} is the velocity of the low frequency Stoneley wave, V_f is the velocity of the fluid in the formation (water in this case), V_s is the S velocity of the formation, ρ is the formation density, and ρ_f is the fluid density.

If the density log has not been recorded, which is the case in this example, it can be calculated from the V_P velocity of the formation using Gardner's equation:

$$\rho = \alpha \times V_P^{\beta}$$

The equations of White and Gardner are used simultaneously to adjust the coefficient α and β of Gardner's equation and to calculate the velocity V_s and density ρ of the formation with the following constraints:

1- The S velocity of the formation must be lower than the P-wave velocity in the fluid.

2- Poisson's ratio must remain in the range 0.3 to 0.5, characteristic of marls and unconsolidated formations.

Figure 3.15 shows, from left to right: the Gardner density, the S velocity estimated from the Stoneley wave velocity, the V_P to V_S ratio and the Poisson's ratio.

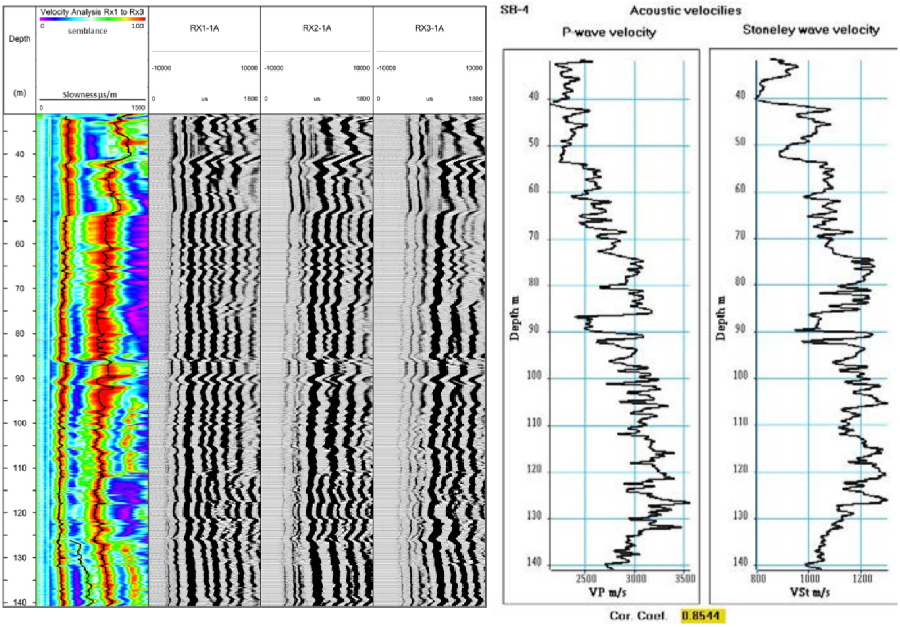


Figure 3.14 *Acoustic logging in slow formation. Left: Velocity panel and acoustic sections with constant offset. Right: P-wave and Stoneley wave velocity logs.*

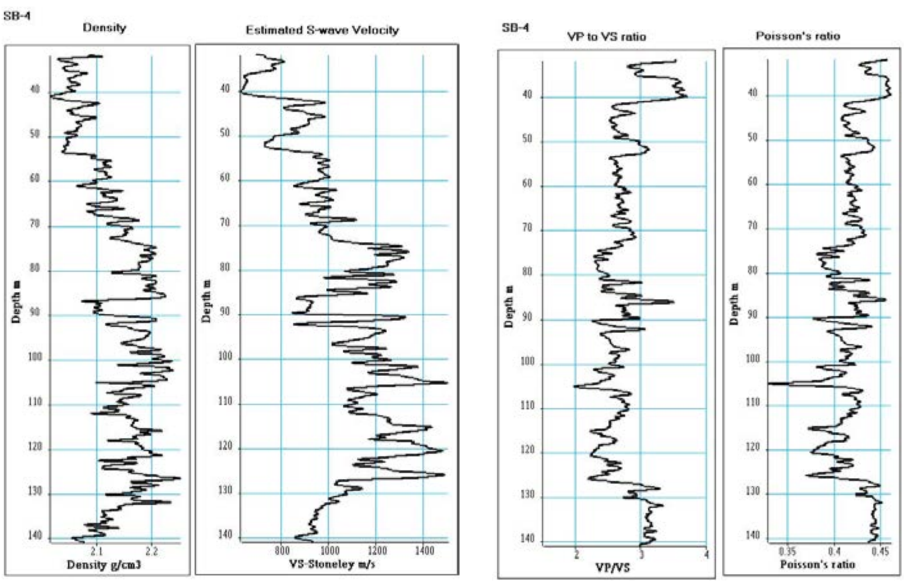


Figure 3.15 *Acoustic logs, from left to right: Density, S velocity estimated from Stoneley wave velocity, V_P to V_S ratio, and Poisson's ratio.*

The response of the Stoneley wave is strongly related to the state of continuity of the well wall. Its transmission is guided by the water or mud interface contained in the borehole and its wall. It is therefore particularly affected by the continuity solution of the borehole wall, while its exploitation and processing highlight its fracturing and degree of opening. The attenuation of Stoneley waves (decrease of amplitude and frequency) is used to characterize the fissured medium. In addition, wave conversion phenomena are observed at the boundaries of the fractured zones. These phenomena are very pronounced on the Stoneley waves, especially in the presence of open fractures.

3.7 Conclusion

Compared to other logging methods, acoustic logging has an equivalent vertical resolution, but a superior ratio of lateral depth of investigation over vertical resolution. Acoustic logging has a lateral investigation in the order of centimeters for interface modes, decimeters to meters for retracted modes, and around ten meters for reflected modes.

Acoustic logging is mainly used to:

- measure the formation velocities (compression and shear) and calculate elasticity moduli (dynamic measurement 2-40 kHz);
- establish a very high resolution time-depth relationship, by integrating the slowness curve (inverse velocity);
- make synthetic seismograms to tie surface seismic reflection (see Chapter 4);
- measure the attenuation and anisotropy (dipole mode) of a formation;
- identify lithology in combination with other logs;
- study fracturing and detect heterogeneities;
- evaluate casing cementation (see Chapters 1 and 4);
- assess porosity and estimate permeability;
- measure dips;
- provide a detailed micro-seismic survey (reflected waves) in the vicinity of the well; these operations are important for highly deviated or horizontal wells.

The following elements must also be considered:

- The acoustic measurement must be made in a well filled with water (mud). It is better to work in open hole (or even a PVC-cased hole). It is desirable to make a continuous measurement of the borehole diameters (logging: calipers) to detect the caved zones. The tool must be centered using centralizers during acoustic measurements.
- Logging speed should be slow (4 to 6 m/min) to respect sampling conditions in terms of distance and to avoid scraping noises created by the centralizers. In general, a frequency filter (low cut: 1 kHz) is used at acquisition to filter these noises.

- Acoustic measurements can be made in steel cased holes, when the casings are perfectly cemented. The presence of resonance phenomena due to poor cementation is used to evaluate cementation (cementation log).
- Well conditions, in the case of poorly cemented cased wells, can make measurements difficult. The waves associated with casing vibrations must be filtered. This processing does not always allow the volume wave characteristics of the formation to be obtained, or the measurement of the formation's parameters.
- Acoustic measurements benefit from the use of long tools (3 to 4 m between the transmitter and the receivers). An operation may encounter difficulties if the lifting system is not high enough. If this is the case, the tool, if flexible, can be bent before being introduced into the well. The tool can also be introduced using constituent parts that can be connected to each other.

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