Drilling Torque-Acoustic Logging: an effective duo for calibrating near -surface seismic data

Introduction

An experimental site, situated in the Cher region (central part of France), is located at the transition from the Triassic to the Jurassic. Recent superficial deposits overlay a carbonate formation with a thickness of about 200 m, covering the basement rock. The carbonate formation can be locally fractured. On the site, two boreholes have been drilled for field experiments. During the drilling, some parameters such as penetration rate and Torque have been continuously recorded. Field experiments include acoustic logging and seismic surveying such as refraction tomography and VSP acquisition.

After a review of seismic imaging of the site, the paper shows how drilling parameters, acoustic logging, and refraction tomography can be merged for obtaining a very high-resolution continuous velocity model from the surface up to the terminal depth of the borehole. We also show the benefit of combining of hybrid seismic methods (reflection seismic processing, refraction tomography), drilling parameters and acoustic logging to extend the previous velocity model, laterally in the vicinity of the borehole.

Seismic imaging

The seismic spread (Figure 1, left) is composed of a receiver spread and a source spread. The receiver spread, displayed in green, is composed of 2 receiver lines. Receiver line direction is called the in-line direction. Distance between receiver lines is 4 m. There are 24 geophones per line. Distance between geophones is 2 m. The source spread, displayed in yellow, is composed of 11 source lines oriented perpendicularly to the receiver lines. 11 shots are fired per line. Distance between shots is 2 m. Distance between source lines is 4 m. The source lines and the receiver lines are oriented perpendicularly. The distance between receiver spread and source spread is 4 m. There is no overlap between the source and the receiver spread. The azimuth of the 3D spread is given by a dotted line displayed in white. The line has been used to implement a 2D seismic profile. The seismic line is composed of 48 geophones, 2 m apart. The receiver spread is fixed. The source is moved and fired between 2 adjacent geophones. For 2D and 3D surveys, the listening time is limited to 250 ms, the sampling time interval is 0.5 ms.

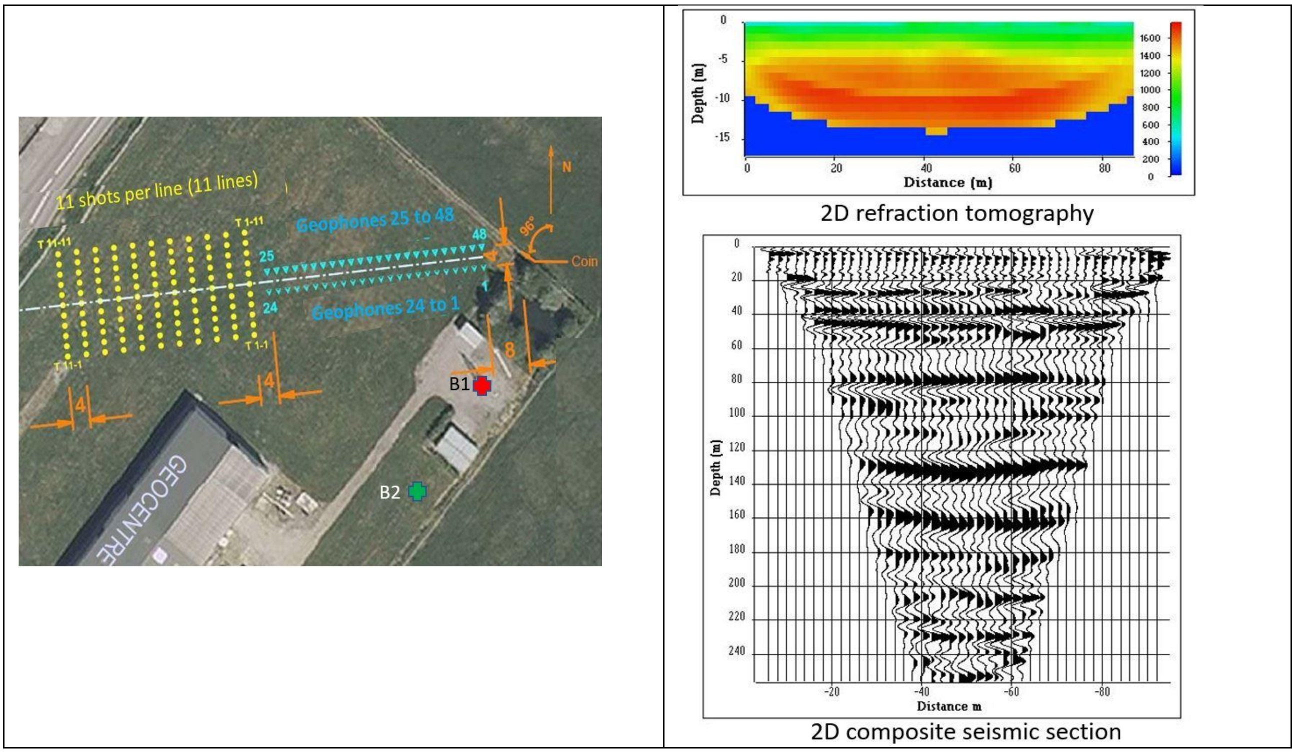

Figure 1 *Seismic spread and boreholes location (B1 & B2) (left). Seismic processing of the 2D line (right)*

The field case presents a refraction-reflection imaging strategy with the capability to evaluate reflectivity information from the acquisition surface (Mendes et al., 2011). The procedure developed to obtain a composite section in depth, already applied successfully on these 2D-3D datasets involves four steps:

- The construction of a depth velocity model from first arrival times, accomplished iteratively by tomographic inversion. 2D refraction tomography results are shown in Figure 2(top right).
- The construction of a time reflectivity section by classical seismic reflection processing.
- The extension up to the surface of the time reflectivity section. It is done by converting the shallowest depth velocity model to time reflectivity, associated with velocity contrasts in the subsurface. The time reflectivity sections require a factor scale before being gathered in a final time reflectivity section (Mendes et al., 2011).
- The depth conversion. The 2D composite section in depth is shown in Figure 1(right).

Acoustic logging

On the site, two boreholes have been drilled. They are indicated by green and red crosses on Figure 1. Borehole B1 is steel cased and cemented. Borehole B2 was drilled in several phases. During the drilling phases, some parameters such as rate of penetration (ROP) and Torque have been continuously recorded. During the first drilling phase up to 78 m depth, B2 is steel cased and not cemented. After the second drilling phase up to 200 m depth, B2 is completed with a slotted PVC casing between 78 and 200 m. Full waveform acoustic logging was run in the 2 boreholes. The acoustic tool is a monopole type flexible tool equipped with a magnetostrictive transmitter (17-22 kHz) and two receivers (offsets:3 - 3.25m Composite acoustic sections are obtained by the merge of acoustic data recorded in borehole B1 (steel cased hole) in the 30 – 78 m depth interval and in borehole B2 (slotted PVC cased hole) in the 78 – 192 m depth interval. Figure 2 shows the 3-m offset acoustic section. Between 0.5 and 0.8 ms, we can see locally resonances which indicate a poor cementation of the borehole. A cemented bound log (CBL) highlights the zones of poor cementation. We can see the refracted P-wave between 0.8 and 2ms, and the Stoneley after 2 ms. The picked times of refracted P-waves allow the computation of the P-wave velocity log (VP) and its associated correlation coefficient log used to evaluate the quality of the measurement. At 120 m depth, we observe a strong delay of the wave trains, associated with a strong decrease of the acoustic P-wave velocity.

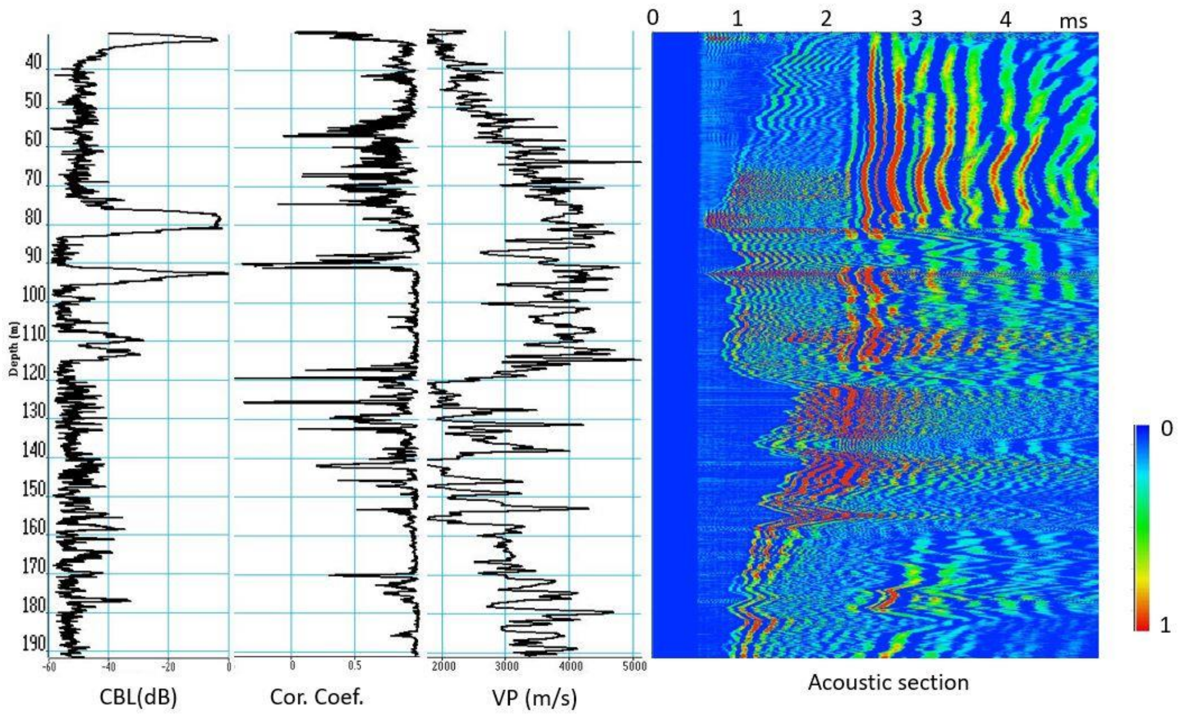

Figure 2 *Acoustic logs and acoustic section.*

Between 120 and 192 m, the acoustic section can be subdivided in 3 acoustic units. The depth intervals associated with the acoustic units are: 120 – 140 m, 140 -152 m, 152 -192 m. In each unit, the acoustic velocity trend increases linearly with depth. We can also observe that the Stoneley waves are locally strongly attenuated.

Drilling parameters

Mechanical specific energy, MSE, is a commonly used measure of drilling performance, MSE, defined as the work required to pulverize a unit of volume of rock with the drill bit, has been often correlated with logging data such as resistivity measurements or velocity measurements given by acoustic logging. If the rotary speed and the bit surface are constant, MSE is proportional to Torque-to-ROP ratio if rotary speed and bit surface are assumed to be constant. In this part, we describe the procedure used to obtain from Torque-to-ROP ratio a continuous velocity log from the surface up to the terminal depth of the borehole. The formation velocity obtained from Torque-to-ROP ratio is referred as to VP-MSE and expressed as follows.

$$VP - MSE = a\frac{T}{ROP} + b \qquad (1)$$

The coefficients a and b are computed to obtain an optimum fit (in the sense of a root mean square error E^2) between acoustic velocities and MSE velocities (VP-MSE). Figure 3 (right) shows the different steps to convert drilling parameters in P-wave velocity.

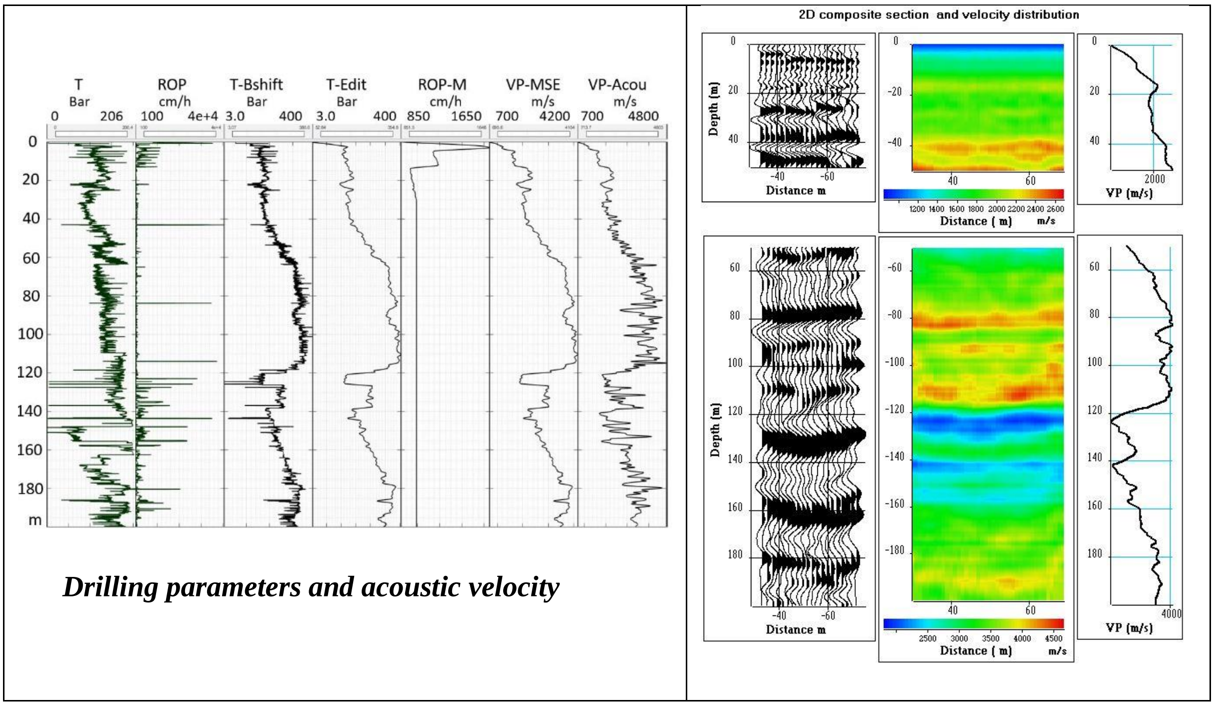

Figure 3 *Drilling parameters and acoustic velocity. From left to right: torque (T), rate of penetration (ROP), torque after block shift (T-Bshift) and editing (T-Edit), model of ROP (ROP-M), P-wave velocity from MSE (VP-MSE), P-wave velocity from acoustic logging (VP-Acou). 2D composite section, seismic velocity distribution and extended velocity log. Top: 0 – 50 m depth interval, Bottom: 50 – 200 m depth interval.*

The P-wave velocity log is the superposition of a short wavelength component and a long wavelength component which gives the trends of variation of the P-wave velocity. A zoning or blocking method is used to evaluate the long wavelength component. The raw drilling logs, Torque (T) and ROP, are corrupted by spikes. In the 30 – 192 m depth interval where the acoustic tool was run, the ROP has been replaced by a constant value (average value: 990 cm/h). To recover acoustic velocity from Torque-to-ROP ratio, the torque log (T, figure 3) must be modified to respect the trends of variation of the P-wave velocity. Based on both visual inspection and results obtained by zoning, the torque log T is subdivided in depth intervals. The intervals are mainly associated with drilling stops and resumptions. In each interval, torque values are modified by adding a constant value ΔP which shifts the log in amplitude (pressure P). Under the assumption that the Torque-to-ROP ratio is proportional to the formation velocity (eq.1), the set of corrections ΔP is adjusted to obtain:

- a corrected Torque which has a high correlation with the blocked acoustic velocity log
- a velocity model, referred to as VP-MSE, which fits (in the sense of a root mean square error) the acoustic velocity log, referred to as VP-Acou, under the assumption that there is a linear relationship between VP-Acou and VP-MSE.

The method of correction is equivalent to the *Block shift method* applied to the sonic log (Boyer et al.,1997). The Torque after block shift correction (T-Bshift, figure 3), has been edited to eliminate the spikes and filtered to have a vertical resolution equivalent to that of the acoustic velocity log (T-Edit, figure 2). In the first 15 m, the ROP, highly corrupted by noise (figure 7, ROP), cannot be combined with the edited torque (figure 3, T-Edit) to compute a velocity distribution. An estimate of the formation velocity is given by refraction tomography (figure 1). Consequently, a smooth ROP model has been recomputed using equation 1, edited torque values and velocity from refraction tomography in the 0-12 m depth interval. In the 12 – 30 m depth interval, the ROP model has been interpolated as seen in figure 3 (ROP-M curve). After calibration with acoustic velocity in the 30 – 192 m depth interval, and validation with tomographic velocity in the 0 – 12 m depth interval, VP-MSE allows a prediction of P-wave velocity in the 12 – 30 m depth interval, with a 10% relative uncertainty. The procedure leads to a high-resolution velocity log from the free surface to the terminal depth of the borehole (figure 3, VP-MSE curve). The 2D depth section has been transformed in a 2D pseudo-velocity section. A calibration operator has been designed to fit the pseudo-velocity trace of the 2D section, located at CMP 50, with the acoustic velocity log extended thanks drilling parameters (figure 3, VP-Acou curve) and resampled at the seismic sampling rate. To extend the 2D velocity distribution over depth, the operator has been applied to the 2D pseudo-velocity section, between CMP 30 and CMP 70. Figure 3 (left) shows from left to right the 2D composite section, the seismic velocity distribution compared with the extended velocity log. In the upper part, the results are shown in the 0 – 50 m depth interval. We can notice a lateral variation of the velocity at 40 m depth. In the lower part, the results are shown in the 50 – 200 m depth. We observe low velocity levels between 120 and 130 m depth and between 140 and 160 m.

Conclusions

The overall procedure for carrying out Full Waveform Acoustic logging (FWAL) experiments is relatively simple and cheap, but the scale investigated does not exceed the close vicinity of the probed borehole. FWAL data are used both to evaluate the quality of borehole cementation and to obtain very high-resolution velocity log. During drilling operation, if drilling parameters such as Torque and rate of penetration (ROP) are recorded, a linear relationship between Torque-to-ROP ratio and acoustic velocity can be computed, in a root mean square sense, to obtain an estimated P-wave velocity from drilling parameters. A specific procedure based on zoning process applied on acoustic data is used to force the torque to respect the trends of variation of the P-wave velocity. After calibration with acoustic velocity in the 30 – 192 m depth interval, and validation with tomographic velocity in the 0 – 12 m depth interval, drilling parameters allow a prediction of P-wave velocity from the surface up to the terminal depth of the borehole, with a 10% relative uncertainty. The field example also shows the benefit of combining hybrid seismic methods (reflection seismic processing, refraction tomography), drilling parameters and acoustic logging to extend the previous velocity model, laterally in the vicinity of the borehole.

References

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