

Geophysics on an experimental site

Géophysique sur site expérimental

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Abstract. APEC (Association Pédagogique et Expérimentale du Cher) has developed an experimental site, situated in the Cher region (France), both for the training of students and for professionals. The site is also used for experimental studies in near surface geophysics. The training in geophysics concerns the acquisition and processing of surface seismic data in 2D or 3D. On the site, two boreholes have been drilled for logging experiments, such as Vertical Seismic Profile (VSP), Full Waveform Acoustic logging (FWAL). During the drilling, some parameters such as rate of penetration (ROP) and Torque have been continuously recorded. The completion of the two boreholes is different to evaluate the behaviour of logging tools with the change of completion (open hole, steel cased hole, slotted PVC cased hole). After a short review of seismic experiments done on the site, the paper is focused on logging data and shows how the completion can modify the answer of the logging tools (acoustic and electrical tools). In acoustic logging, the comparison of acoustic data recorded in slotted PVC cased hole and in open hole shows that the prediction of shear formation velocity from Stoneley waves can be done in open hole. In case of a completion with slotted PVC, the joints of PVC casing disturb the resistivity measurements. A specific procedure has been developed to filter the casing disturbances.

Résumé. APEC (Association Pédagogique et Expérimentale du Cher) a développé un site expérimental, situé dans le Cher (France), pour la formation d'étudiants et de professionnels. Le site est également utilisé pour des mesures expérimentales en géophysique de proche surface, notamment des acquisitions sismiques en 2D ou 3D. Sur le site, deux puits ont été forés, pour acquérir des données de puits de type Profil Sismique Vertical (PSV) ou diagraphie acoustique en champ total. Pendant le forage, certains paramètres tels que le taux de pénétration et le couple ont été mesurés en continu. La complétion des puits est différente dans le but d'évaluer le comportement des outils de logging en fonction de la complétion (trou ouvert, trou avec un couvage acier, trou équipé d'un PVC crépiné). Après une revue des différentes expérimentations sismiques réalisées sur le site, nous présentons les résultats obtenus en diagraphie acoustiques et montrons

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comment la complétion d'un puits peut modifier la réponse d'un outil de logging. En acoustique, la présence d'un casing PVC crépiné perturbe la réponse ondes de Stoneley et l'estimation de la vitesse S de la formation à partir de ces ondes en est altérée. En électrique, les joints de tubage d'un casing PVC crépiné créent des artefacts qui doivent être filtrés pour rendre la mesure de résistivité exploitable.

1 Introduction

An experimental site (Figure 1), situated in the Cher region (central part of France), is located at the transition from the Triassic to the Jurassic.

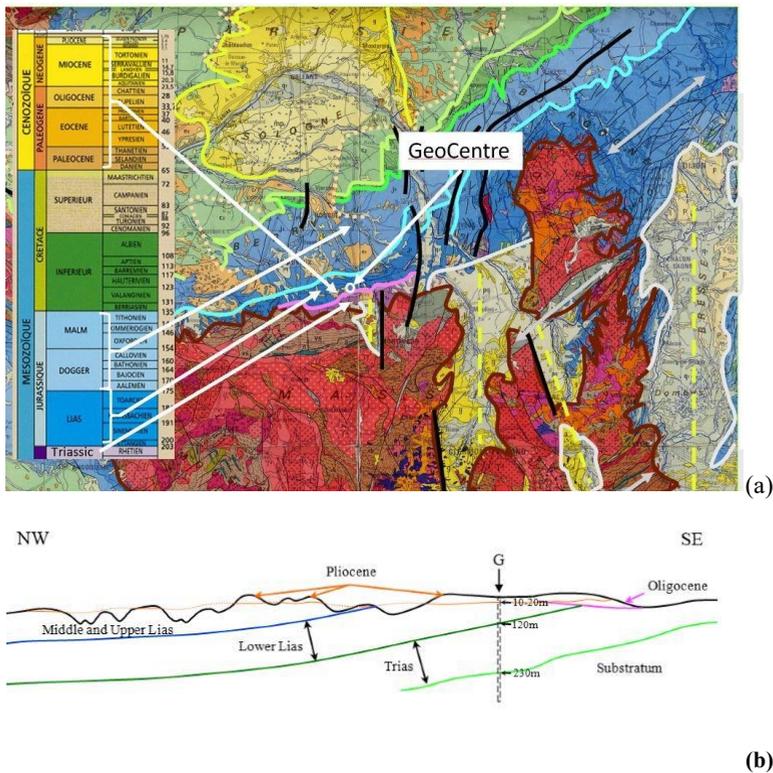


Fig. 1. The experimental site: (a) location of the site and geological map. (b) a simplified geological cross-section oriented North-West South-East established by Jean Luc Bouchardon (personal communication, 2007), After [1].

Recent superficial deposits overlay a sedimentary formation with a thickness of about 200 m. The sedimentary formation is mainly composed of limestones up to 120 m and sandstones with some argillite and dolomite intercalations between 120 m and 200 m. The site belongs to Geocentre, a company involved in geotechnical studies and drilling. The site has been developed both for the training of students and for professionals, it is also used for experimental studies in near surface geophysics. The training in geophysics concerns the acquisition and processing of surface seismic data in 2D or 3D [1]. On the site, two boreholes (B1 and B2) have been drilled (Figure 2a). Boreholes allow the acquisition of well seismic data such as vertical seismic profiles (VSP) and logging data such as full wave form acoustic data [1].

After a short review of seismic experiments done on the site, the paper is focused on logging data and shows how the borehole completion can modify the answer of the logging tools (acoustic and electrical tools).

2 Seismic imaging

The surface seismic spread (Figure 2, a) is composed of a receiver spread and a source spread. The receiver spread, displayed in green, is composed of 2 active lines of receivers. 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 CMP domain (white rectangle in figure 2a) is composed of 11 CMP lines (1 m apart) in the receiver line direction with 44 CMP (1 m apart) per line [2]. 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 (Figure 2, c). The seismic line is composed of 48 geophones, 2 m apart. The receiver spread is fixed. The source (Figure 2, c) 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. A vertical seismic profile (VSP) was recorded in borehole B1 in the 25 -90 m depth interval (figure 2a).

The field case presents a refraction-reflection imaging strategy with the capability to evaluate reflectivity information from the acquisition surface [3]. 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.
- The construction of a time reflectivity section by classical seismic reflection processing. The processing is carried out with the SPW (seismic processing workshop) software developed by Parallel Geoscience [4].
- 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 [3].
- The depth conversion using VSP data [5,6] recorded in borehole B1 (figure 2a). The measurement of the arrival time of the first down-going waves propagating at close-to-normal incidence is used to provide both a time versus depth law and a velocity distribution in the subsurface. After processing, the VSP provides a seismic trace (VSP corridor stack trace) directly comparable to the surface seismic section passing in the vicinity of the borehole. VSP is used to predict events (reflectors or heterogeneities) located beneath the borehole. The law of VSP time versus depth, $t = f(z)$, can be used to convert the time seismic sections into seismic sections in depth scale. The CMP point #27 of the in-line seismic section #3 (extracted from the 3D block) is located approximately 40 m away from the borehole B1 in which the VSP has been recorded. The VSP stacked trace, duplicated five times, is inserted in the in-line section #3 at the CMP location #27 (figure 2b). The results are shown in depth (figure 2b). The 2D composite section in depth is shown in Figure 2d.

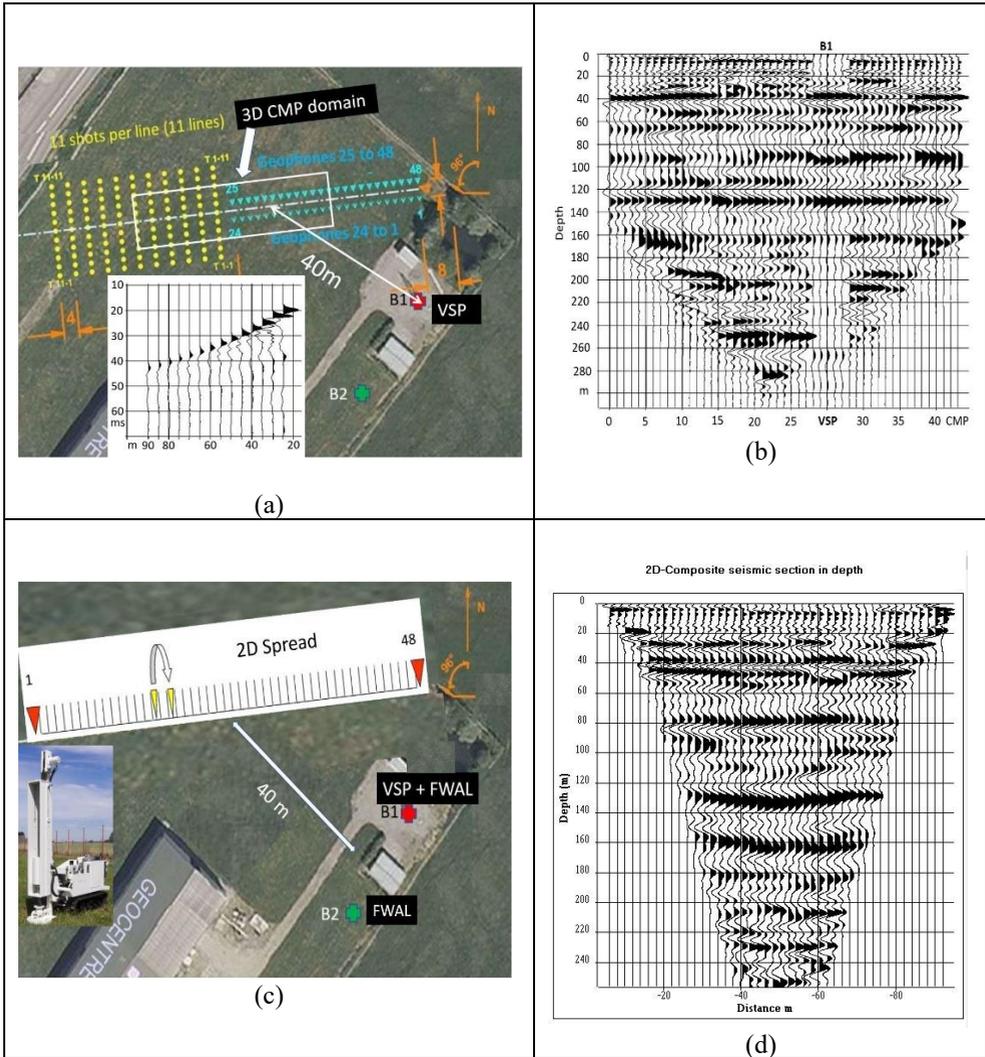


Fig. 2. Seismic imaging: (a) 3D seismic spread, borehole locations (B1 and B2), VSP recorded in B1, (b) 3D composite inline section in depth after calibration by VSP corridor stacked trace, (c) 2D seismic spread and view of the seismic source, (d) 2D composite section in depth. After [1]

3 Full wave form acoustic logging

As indicated earlier, two boreholes are available at the site. They are marked by green and red crosses in figure 2a. Borehole B1 was drilled by Geocentre in 2006 but is now fully steel cased and cemented. Borehole B2 was drilled by Geocentre-Forsol in two phases between September 2019 and September 2020. During the drilling phases, some parameters such as the rate of penetration (ROP) and torque were continuously recorded [7]. The first drilling phase from the surface up to 78 m depth resulted in a steel cased but not cemented borehole. Re-handling the borehole within the second drilling phase allowed to reach the depth of 200 m in open hole with a borehole completely cored between 78 and 200 m, then equipped with a slotted PVC casing.

In borehole B1, a vertical seismic profile (VSP) and Full waveform acoustic data were recorded. The example (figure 2a) shows that it is possible to record successfully VSP in cemented steel cased hole. In borehole B2, only Full waveform acoustic data were recorded.

To evaluate the borehole conditions, a full wave form acoustic tool was run in the two boreholes. The acoustic tool [8] is a monopole type flexible tool with a small diameter (50 mm). 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)).

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 slow formations, they are more dispersive and sensitive to the S-wave parameters of the formation. Stoneley waves are used to evaluate the shear velocity of slow formations.

Furthermore, on constant offset acoustic sections, we can observe coherent slanted events. The slanted events, conventionally named criss-cross events, are refracted events reflected on the edges of geological discontinuities (acoustic impedance discontinuities), such as fractures.

The acoustic tool is used here with its far offsets' configuration. The sampling interval in depth is 2 cm. The sampling interval in time is 5 μ s and the listening time is 5 ms. Figure 3 shows the 3m-offset acoustic sections (R1 section) recorded in boreholes B1 and B2.

The acoustic section recorded in borehole B1 shows:

- Synchronization signals in the time interval 0 - 0.5 ms. These electronic signals have no geological meaning.
- Resonances in the time interval 0.6 - 0.8 ms, locally in depth. These resonance phenomena are related to poor cementation between the casing and the formation. In the 75 to 90 m depth range, the resonances interfere with the acoustic signals that propagate through the formation. The resonance level can be estimated by calculating the energy of the acoustic signal over the time interval
- Formation refracted waves. The first arrival times of these waves vary from 1.8 to 0.7 ms in the depth range 30 m to 80 m. This change in arrival time indicates a gradual increase in formation velocity with depth. There is also a change in the character of the acoustic signal: low frequency in the range 30 to 65 m, high frequency, and noise for depths greater than 65 m.
- Stoneley waves. These wall waves with high amplitudes, which appear after 2.4 ms, are influenced by casing.

The acoustic section recorded in borehole B2 shows:

- Strong resonances in the time interval 0.6 – 3 ms, between 29 m and 78 m. The resonances with extraordinarily strong amplitude without attenuation clearly indicate that there is no coupling between the steel casing and the geological formation. B2 is an uncemented cased hole up to 78 m depth. Consequently, this part of the borehole cannot be used to do any type of logging for geological studies.
- Stoneley waves and fluid waves in the depth range 78 – 125 m. The Stoneley waves with high amplitude and low frequency appear after 2.4 ms. The high frequency fluid waves appear between 2 and 2.4 ms. Refracted P-waves, which have low amplitude in comparison with the amplitude of Stoneley waves, are not visible without amplification. B2 is open hole between 78 and 125 m.

- Resonances between 88 and 92 m. This indicates the presence of a piece of casing in the open hole part of the well.

At 125 m depth, we observe a collapse of the borehole, probably due to tectonic features (fractures), which prevents taking logging measurements at depths greater than 125 m. B2 was redrilled and completed with a slotted PVC between 78 and 200 m (figure 4).

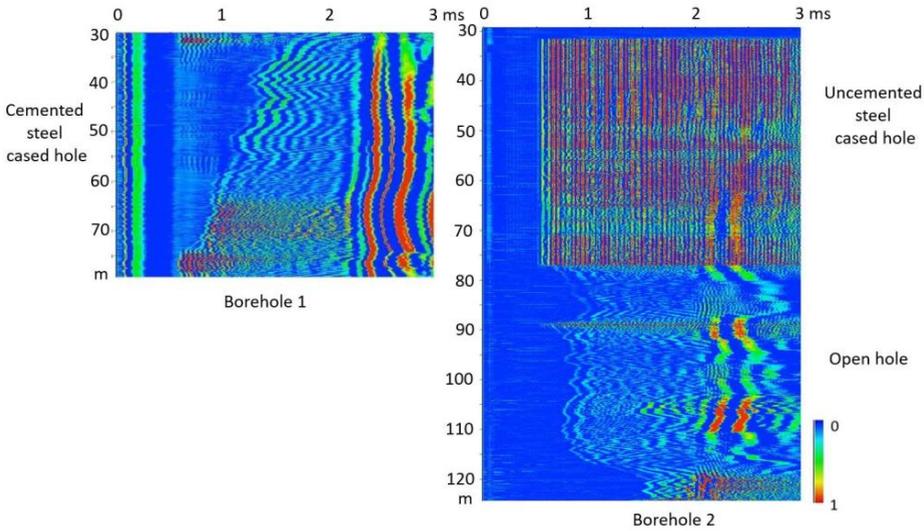


Fig. 3. Acoustic sections in boreholes B1 and B2 (phase 1).

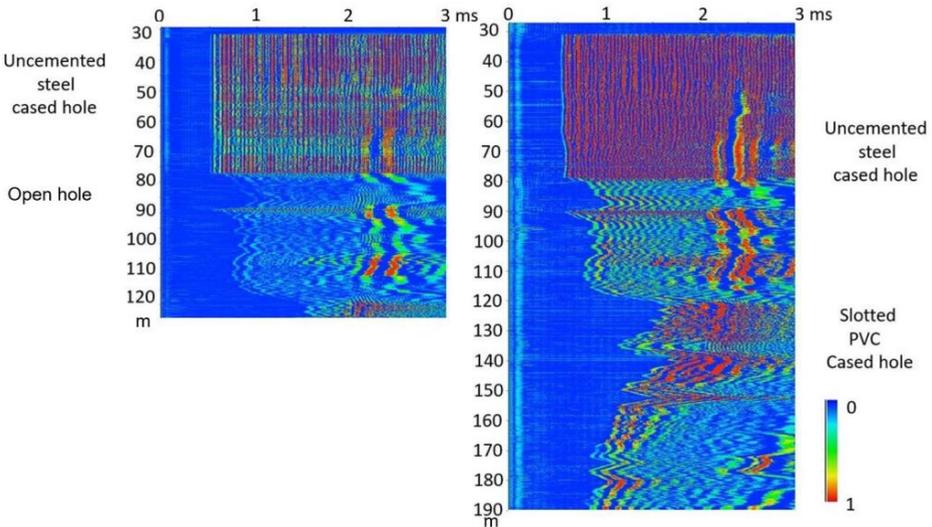


Fig. 4. Acoustic sections in borehole B2 (phases 1 and 2)

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 5 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) in the 30-192 m depth interval. The associated correlation coefficient log is used to evaluate the quality

of the measurement [1]. At 120 m depth, we observe a strong delay of the wave trains, associated with a strong decrease of the acoustic P-wave velocity.

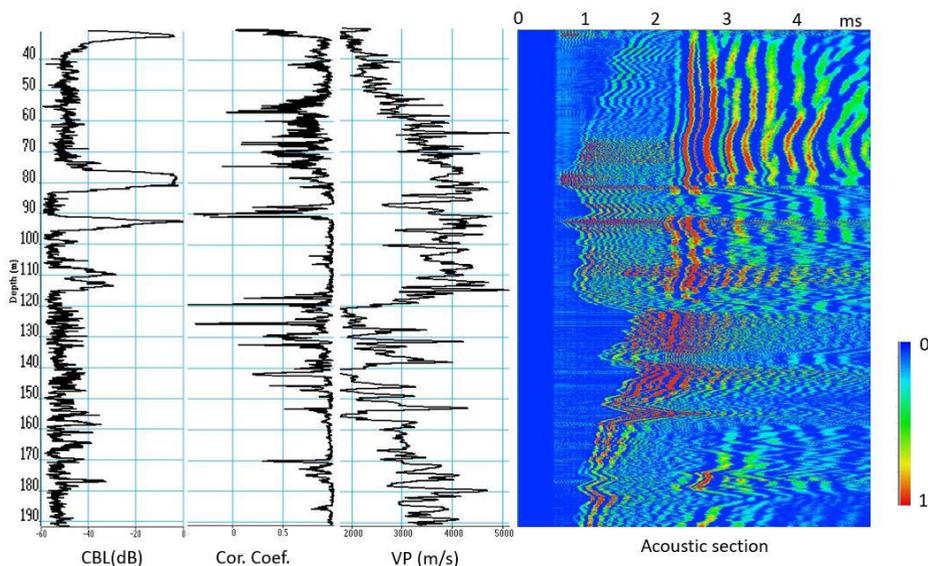


Fig. 5. Acoustic logs and full wave form composite acoustic section. After [1].

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.

3.1 Full wave form acoustic data processing

Conventional processing of acoustic data (Mari, 2020) enables time-depth relationship and velocity logs to be obtained at the borehole, as well as certain mechanical parameters such as the Poisson's ratio.

The processing sequence includes :

1. Editing (elimination of poor-quality recordings) and filtering of acoustic sections. The presence of criss-cross events can lead to mispicking of the arrival times of the different wave trains as well as error in their amplitude measurement. Apparent velocity filters applied on constant offset sections allow the extraction of criss-cross events.
2. Calculation of acoustic velocities by picking the arrival times of the different wave trains or by velocities scanning and semblance processing. In our case, due to the configuration of the acoustic tool, only two receivers R1 and R2 are used simultaneously, R1 and R2 being at 3 m and 3.25 m respectively from the acoustic source. If formation velocities are obtained by measuring the arrival time difference of the different wave trains at the different receivers of the tool, velocity logs can be computed in 2 steps. In a first step, the time difference δt between the acoustic signals observed on the receivers R1 and R2 gives a raw P-wave velocity log (figure 5). In a second step, the correlation log between the acoustic signals observed on the receivers R1 and R2, after compensation for δt is computed (figure 5). A high value of the correlation coefficient indicates a strong similarity between the two signals and a good velocity measurement. The correlation coefficient is used to edit velocity logs. If the correlation is smaller

than a given threshold (70% for example), the velocity value is cancelled and replaced by interpolation.

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). On acoustic sections, in the time interval where the resonances associated with the presence of casing are observed, the resonance level can be estimated by calculating the energy of the acoustic signal over the time interval. The normalized acoustic signal energy as a function of depth is an acoustic log that is used to provide a log indicative of cementation quality, conventionally referred as CBL (cemented bound log, figure 5).

Optional:

1. Measurement of the amplitudes of the different wave trains and calculation of the amplitude or energy and attenuation logs. The acoustic distortion of the refracted P-wave is measured by a qualitative dimensionless attribute called Shape Index (I_c) attribute, introduced by Lebreton in 1983. I_c is obtained calculating the ratio A_2+A_3 to A_1 where A_1 , A_2 and A_3 are the amplitudes of first three arches of the refraction wavelet. I_c variation indicates the presence of wave interferences, fractures, or permeable zones [6]. If I_c is measured on acoustic section after filtering of criss-cross events, I_c is a physical parameter which is related to refracted P-wave propagation in the formation (attenuation, phase change). The distribution of criss-cross events observed on a constant of offset section can be quantified by an associated normalized energy log (I-Criss).
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 or Raymer-Hunt-Gardner equation, ...)
4. Calculation of elastic modules (geomechanical: choice of models used)

3.2 Acoustic logging in borehole B1

Figure 6 shows the acoustic section R1 recorded in the 30-78 m depth interval before and after filtering of the crisscross events. The resonances due to the casing are cancelled by a mute given by the picked times of the refracted wave. Figure also shows the criss-cross events and the associated criss-cross index log (I_{criss}). Figure 7 shows the acoustic logs extracted from the acoustic data. We can see from left to right: P-wave energy, shape index I_c , criss-cross index (I_{criss}), VP velocity and its associated correlation coefficient. More than 80 % of P-wave velocity values have a correlation coefficient greater than 0.7.

3.3 Acoustic logging in borehole B2 (open hole)

Figure 8 shows the acoustic sections R1 and R2 recorded in the 78-124 m depth interval, section R1 is displayed before and after filtering of the crisscross events, section R2 is displayed after filtering of the crisscross events. The resonances due to the casing are cancelled by a mute given by the picked times of the refracted waves. Figure 8 bottom left also shows the criss-cross events. Figure 9 shows the acoustic logs extracted from the acoustic data. We can see from left to right: Total wavefield energy, Stoneley-wave energy and attenuation, Stoneley-wave velocity, and its associated correlation coefficient (more than 80 % of Stoneley-wave velocity values are associated with a correlation coefficient greater than 0.8), shape index I_c , criss-cross index I-Criss, P-wave velocity and its associated correlation coefficient (more than 80 % of P-wave velocity values are associated with a

correlation coefficient greater than 0.7). We can notice that, below 120 m, the Stoneley wave velocity is 1500 m/s which corresponds to fluid velocity and consequently to a fluid wave.

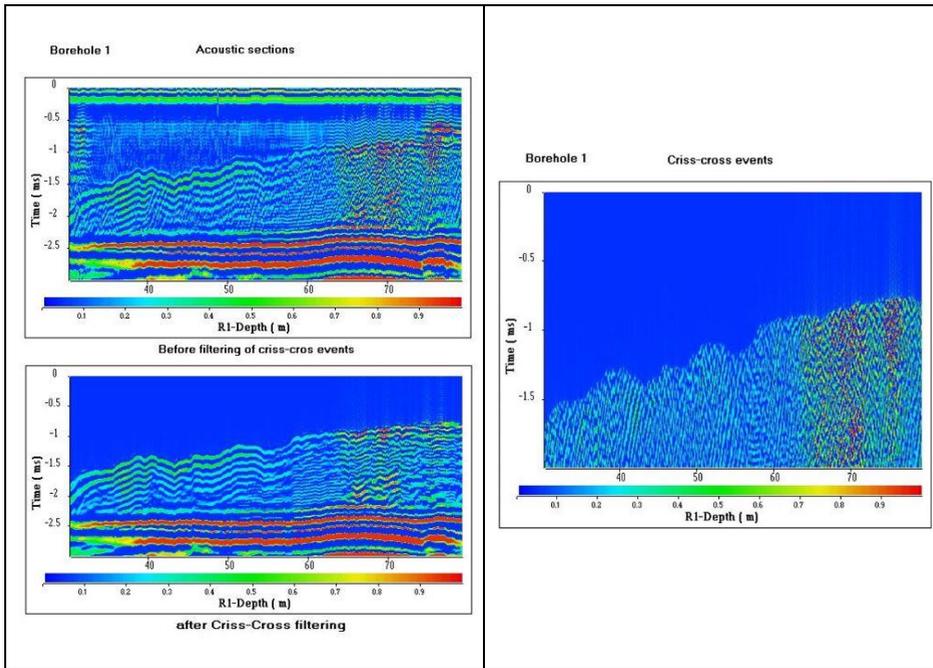


Fig. 6. Acoustic sections recorded in borehole B1

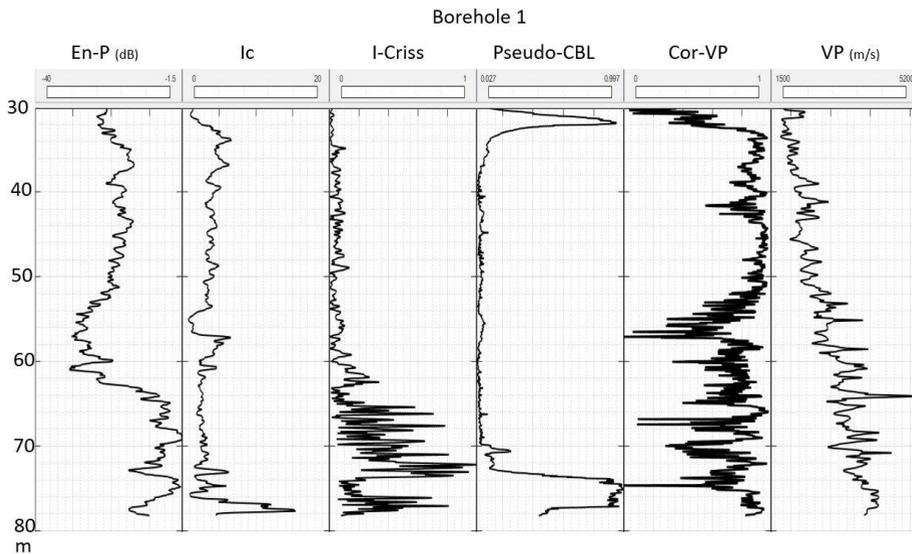


Fig. 7. Acoustic logs in borehole B1

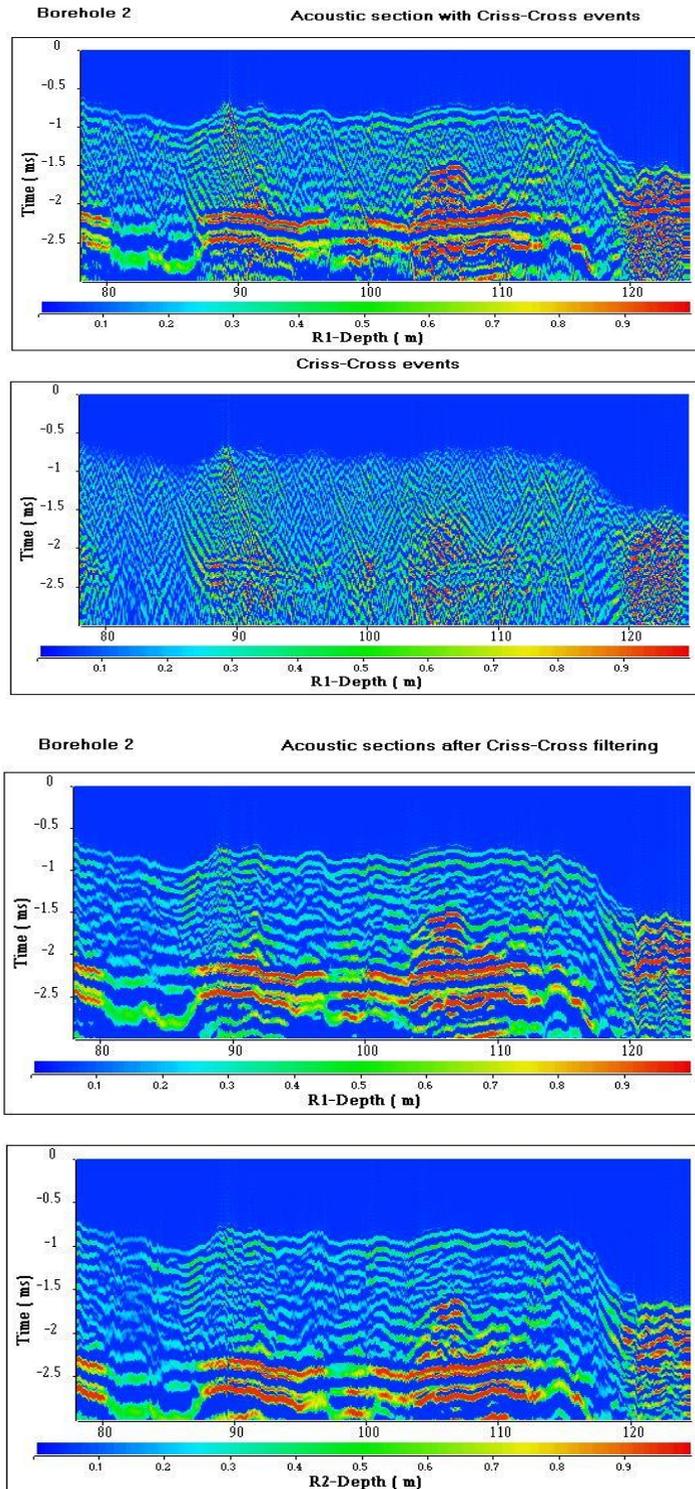


Fig. 8. Acoustic sections recorded in borehole B2 (open hole)

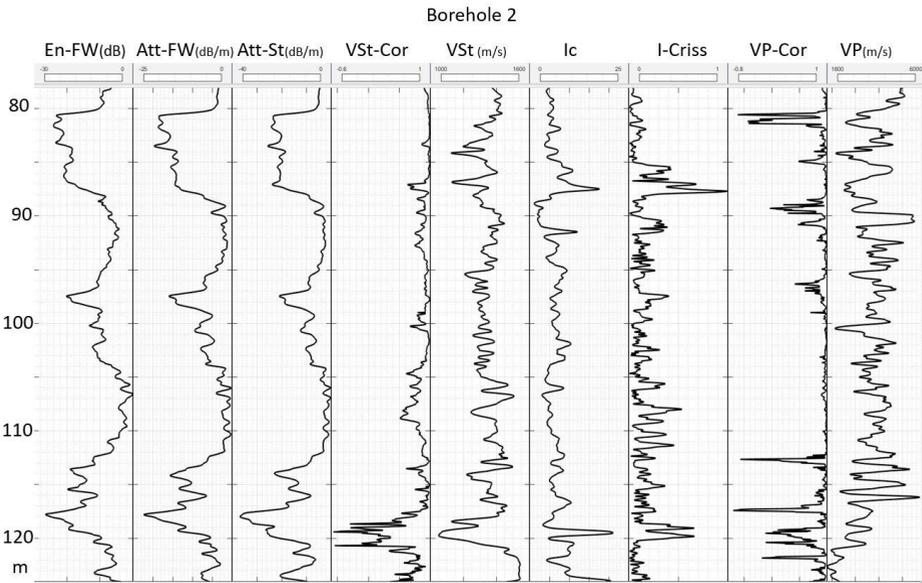


Fig. 9. Acoustic logs in borehole B2 (open hole)

On the acoustic section, we can see converted refracted S-wave, between 1.5 and 2 ms in the 104 – 110 m depth interval. In the depth interval, the acoustic data have been processed to obtain the shear parameters of the formation: S-wave velocity and attenuation, Poisson’s ratio (figure 10). The geological formation being acoustically a slow formation, except in the 104 – 110 m depth interval, its shear wave velocity VS is estimated from Stoneley-wave velocity in the 78 – 120 m depth interval. According to White [9], VS can be derived from a simplified version of the dispersion equation that relates shear-wave velocity (VS), low-frequency Stoneley velocity (VSt), fluid velocity (Vf), formation and fluid densities (ρ and ρ_f , respectively):

$$\frac{1}{V_{St}^2} - \frac{1}{V_f^2} = \frac{\rho_f}{\rho} \cdot \frac{1}{V_S^2}$$

An estimation of ρ can be given by a Gardner equation: $\rho = \alpha VP^\beta$

The α and β Gardner coefficients have been adjusted, using the dispersion equation in the 104 – 110 m depth interval, where shear wave velocity VS is measured. α has been fixed to 0.3 and β to 0.25. The shear velocity (VS) estimation from Stoneley-wave velocity in the 78 – 120 m depth interval is done under the following constraints:

- VS < 0.65 VP
- Poisson’s ratio must range between 0.25 and 0.45.

Figure 11 shows the acoustic logs in the 78 – 120 m depth interval: Stoneley-wave energy and attenuation, shape index Ic, criss-cross index I-Criss, Poisson’s ratio, estimated shear wave velocity VS, Stoneley velocity, P-wave velocity, and its associated correlation coefficient.

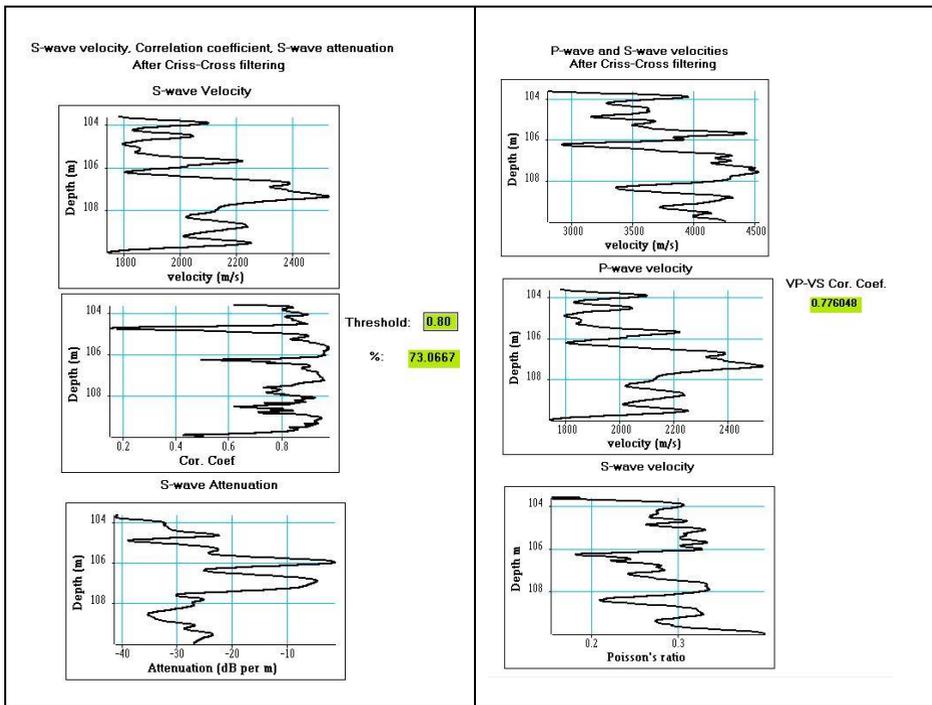


Fig. 10. S-wave acoustic logs in borehole B2 (open hole)

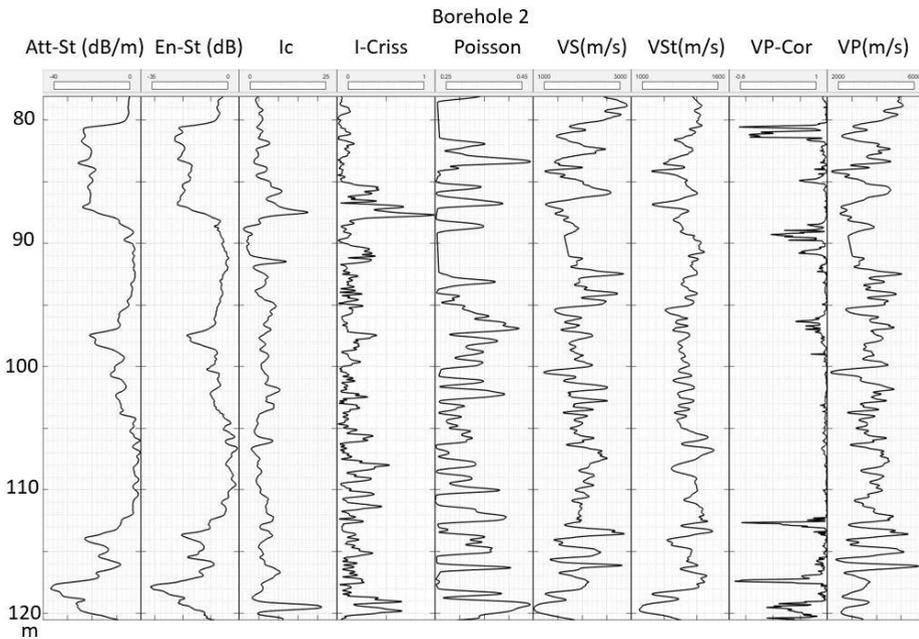


Fig. 11. Acoustic logs for mechanical studies in borehole B2 (open hole)

3.4 Acoustic logging: composite logs

The composite acoustic sections (figure 5) have been processed to obtain additional logs such as shape index log and energy log (figure 12) to compare the acoustic response with the type of completion (steel cased hole and slotted PVC cased hole). We can notice that the shape index has a lower value in steel cased hole than it has in slotted PVC cased hole. It detects the presence of a piece of steel casing in the 88-90 m depth interval.

The velocity log has been converted in acoustic porosity using the Wyllie's formula [10]. We can notice a decrease of shape index I_c with an increase of porosity.

The acoustic velocity log shows to main units: the first one between 30 and 120 m, the second one between 120 and 192 m. The first one is associated with Liassic and the second one is associated with Triassic, the limit between the 2 units is located at a depth of 120 m as indicated by the gamma ray log (GN, figure 12).

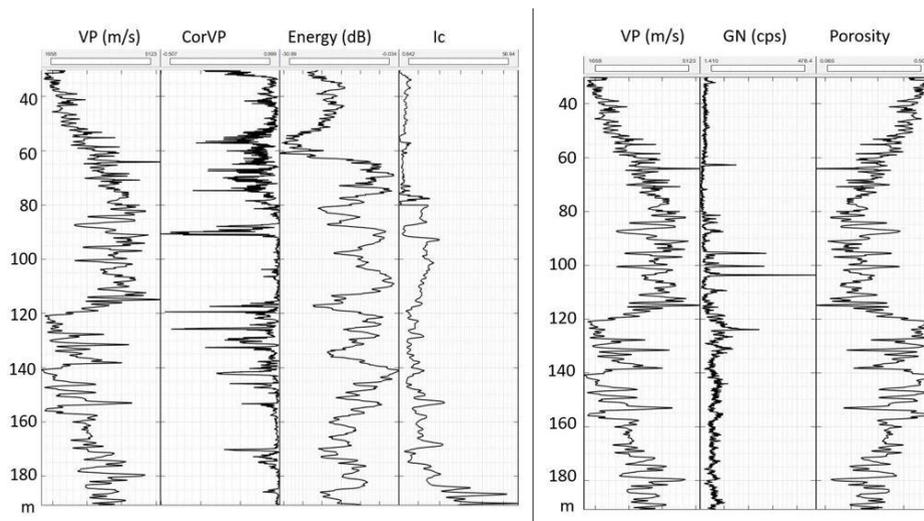


Fig. 12. Acoustic logs (VP, Cor-VP, Energy, I_c , Porosity) and Gamma ray (GN)

4 Resistivity logs

Resistivity logs have been recorded by Soleo-logging in borehole B2 in the open hole part. The electric logging probe provides long (64", LLD) and short (16", LLS) normal resistivity data. Figure 13 shows the results obtained in open hole in the 78 – 120 m depth interval. The resistivity logs have a very high correlation coefficient (close to 1), the correlation between resistivity log and acoustic velocity log is poor (0.3). The vertical resolution of the acoustic log is much higher than the one of the resistivity logs. Consequently, it seems difficult to do a link between the two sets of logs.

In full or slotted PVC cased holes, formation resistivity is usually measured using induction tools. On an experimental basis, resistivity logs have been recorded after the second phase of drilling, borehole B2 being completed with a slotted PVC casing between 78 and 200 m. The resistivity logs are shown in figure 14. The logs are highly corrupted by the joints of the PVC casing. The joints introduce spiked zones on the logs. The distance between the 2 spiked zones corresponds to the length of a PVC casing element. To filter the spiked zones, a mask is applied on the resistivity logs and the missing resistivity values are interpolated. The mask is obtained by applying a threshold on the second derivative of the resistivity log.

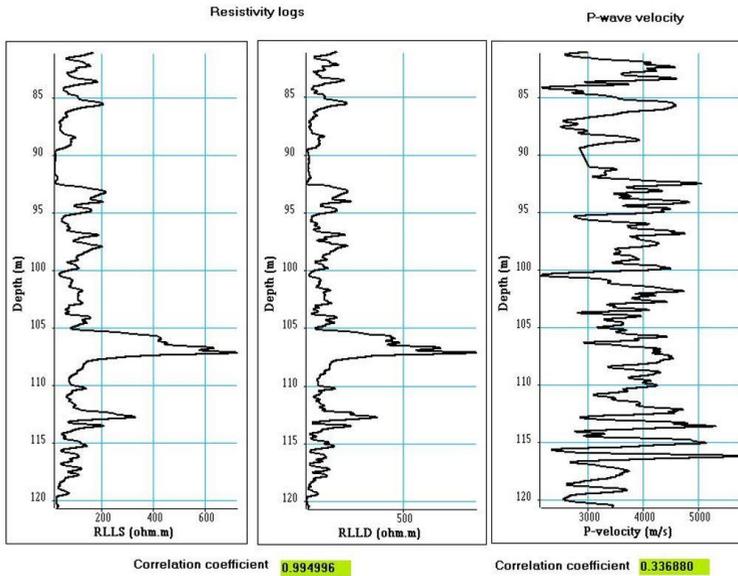


Fig. 13. Resistivity logs (LLS, LLD) and acoustic velocity in borehole B2 (open hole)

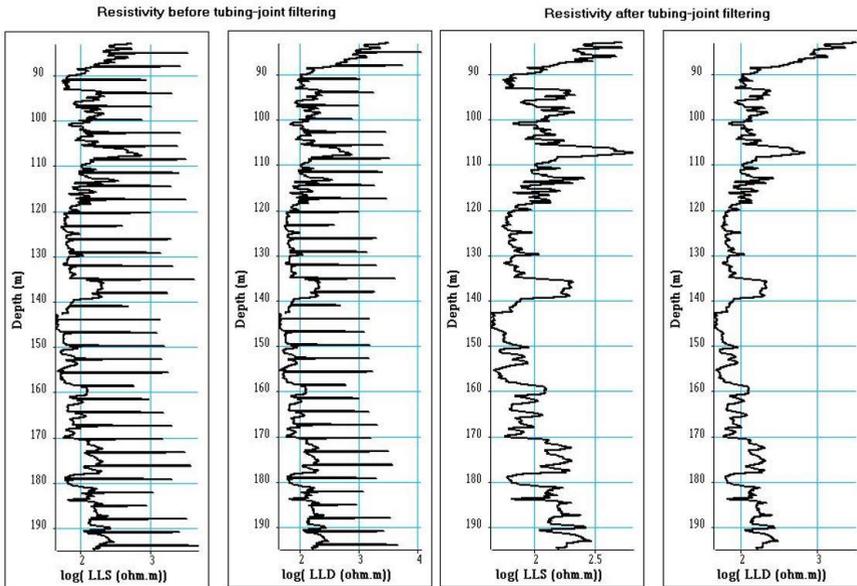


Fig. 14. Resistivity logs in borehole B2 (slotted PVC cased hole)

The resistivity logs after tubing joint filtering are shown in figure 14 (right part). To validate the efficiency of the filtering, the resistivity logs are compared in the open hole part. The LSS resistivity log in open hole and the LLS resistivity log in Slotted PVC cased hole after tubing joint filtering have a high correlation coefficient (0.84). The 2 logs are shown in figure 15a (left). The LLS and LLD logs after tubing joint filtering are very similar and stackable (figure 15a, right). The correlation coefficient between the two logs is very high (0.92).

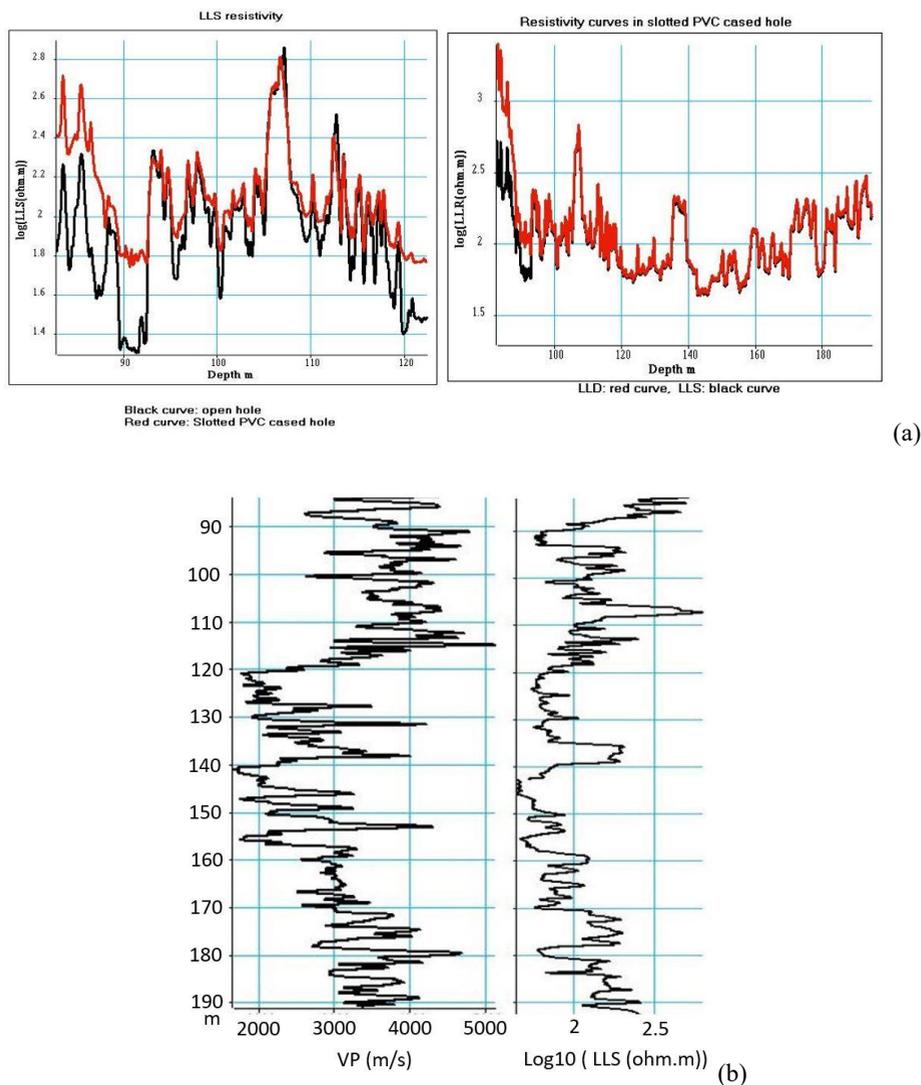


Fig. 15. Resistivity logs after tubing joint filtering in borehole B2 (slotted PVC cased hole): (a) comparison between LLS log in open hole and in slotted PVC cased hole, comparison between LLS and LLD logs in slotted PVC cased hole. (b) comparison between acoustic velocity log and resistivity log (LLS)

Figure 15b shows a comparison between the acoustic velocity log and the LLS resistivity log after tubing joint filtering. The LLS log is displayed with a logarithmic scale. We can notice that the 2 logs have the same general trend and can be subdivided in geophysical units: 85 - 120 m, 120 - 140 m, 140 - 160 m, 160 - 170 m, 170 - 192 m. The example shows that it is possible to obtain formation resistivity in slotted PVC cased boreholes. However, it is recommended to run induction tool.

Conclusion

APEC (Association Pédagogique et Expérimentale du Cher) has developed an experimental site both for the training in geophysics of students and for professionals. The site is currently used for experimental studies in near surface geophysics and logging experimentation.

Two boreholes (B1 and B2) are available at the site. Borehole B1 which reaches a depth of 80 m is now fully steel cased and cemented. Borehole B2 was drilled in two phases. The first drilling phase from the surface up to 78 m depth resulted in a steel cased but not cemented borehole. Re-handling the borehole within the second drilling phase allowed to reach the depth of 200 m. Borehole B2 was then equipped with a slotted PVC casing. The changes in borehole completion (open hole, steel cased cemented or uncemented hole, slotted PVC cased hole) allow to evaluate the behavior of logging tools versus completion.

The paper has briefly shown that the hybrid seismic imaging tool is valuable for obtaining information about the reflectivity for targets located in the near and/or extremely near surface. Based on a four-step procedure, the processing of refracted and reflected waves provided two sections, which after gathering produced in a first step an extended time reflectivity section starting from the surface and in a second step a section in depth after calibration with VSP data.

The paper has been focused on logging data and has shown how the borehole completion can modify the answer of the logging tools (acoustic and electrical tools). For full waveform acoustic logging (FWAL), the analysis has been done both on acoustic sections and acoustic logs. A quick look on acoustic sections allows both to identify the different wave trains and to appreciate their properties (amplitude variation, shape distortion, frequency content, loss of continuity...) which can indicate the presence of tectonic features such as fractures. The visual observations have been quantified by acoustic logs (velocity, energy, shape index, criss-cross index...). The Stoneley waves, very sensitive to the borehole wall conditions (type of completion), can be fruitfully used in open hole to estimate the shear velocity of the formation, after local calibration on shear velocity measurement estimated from converted refracted S wave. Concerning the resistivity log, it has been shown that the logs are highly corrupted by the joints of a PVC casing. The joints introduce spiked zones on the logs. A specific procedure has been developed to filter the disturbance created by the joints. The efficiency of the filtering is done by comparing logs recorded in open hole with logs recorded in slotted PVC cased hole after tubing joint filtering. A comparison between the acoustic velocity log and the LLS resistivity log after tubing joint filtering has shown that the 2 logs have the same general trend and highlight geophysical units. However in full or slotted PVC cased holes, it is recommended to run induction tools to measure formation resistivity.

The paper has shown a part of the experiments conducted on the site and only a part of the results.

During the drilling phases of borehole B2, some parameters such as the rate of penetration (ROP) and torque were continuously recorded, a procedure has been developed to estimate the velocity of the formation (from the ground surface to the terminal depth of the borehole) from the torque to ROP ratio after calibration with acoustic velocity log [7].

Borehole B2 has been cored during the different drilling phases. The cores are preserved in a core library situated on the site. Anthony Hardy (Geocentre Forsol) has done a brief description of the cores [1]. Criss-cross events observed on acoustic sections and acoustic velocity logs have been used to develop an algorithm to automatically detect the presence of fractures. The results obtained with the algorithm have been validated by comparison with cores [1].

In the slotted PVC cased hole of B2, a flowmeter has been run by Soleo-logging. Flow log measurements have confirmed the occurrence of flowing horizons that were previously marked by both seismic and acoustic data [1]. Next experiments will be done to evaluate the potential of acoustic data to detect flows by comparing active acoustic data (acoustic tool with active source) with passive acoustic data (acoustic tool without active source).

With 2 boreholes (with different completions) and core data available, the experimental site (apecvds@orange.fr) gives geoscientists the opportunity to conduct seismic and logging experiments.

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References

1. J. L. Mari, F. Delay, G. Porel, P. Gaudiani, Characterizing flow in the first hundred-meter depth of a fractured aquifer using hybrid seismic methods, acoustic logging, and flow log measurements, *Oil & Gas Science and Technology – Rev. IFP Energies Nouvelles* **76**, 62, <https://doi.org/10.2516/ogst/2021048> (2021)
2. J.L. Mari, M. Mendes, L. Azevedo, Imaging of the first hundred meters of the subsurface using hybrid seismic methods and acoustic logging, *Parallel Geoscience*, technical paper, www.parallelgeo.com, (2020)
3. M. Mendes, J.L. Mari J.L. Description of near surface geological structures combining refracted and reflected seismic data, in: Proceedings of the 73rd EAGE Conference: Unconventional Resources and the role of Technology, 73rd EAGE Conference & Exhibition incorporating SPE EUROPEC, Vienna, Austria, 23-26 May 2011, DOI: 10.3997/2214-4609.20149307, (2011).
4. J.L. Mari, D. Herold, Seismic Processing Tutorial: using the SPW Software, EAGE Publications, ISBN: 9789462821507, (2015)
5. B.A. Hardage, Vertical Seismic Profiling, Part A: Principles. Geophysical Press, London, 509 p., (1984).
6. J.L. Mari, C. Vergniault C., Well seismic surveying, and acoustic logging. EDP Sciences, 138 p., DOI: 10.1051/978-2-7598-2263-8, (2018)
7. J. L. Mari, K. Gestin, P. Gaudiani, Drilling torque – Acoustic logging: an effective duo for calibrating near- surface seismic data, paper number: 2409, 82nd EAGE annual conference & exhibition, Amsterdam, The Netherland (2021) <https://spotlight-earth.com/eage-2021-x-paper-3/>
8. P. Gaudiani, Système améliorant les procédés de mesures acoustiques, Brevet (Patent) : 79 27528, Service des Brevets, 20 bis rue de Leningrad, 75800 Paris cedex 08, (1979)
9. J.E. White, Seismic waves: radiation, transmission and attenuation, McGraw Hill, New York (1965)
10. M.R. Wyllie, R.J. Gregory, H.F. Gardner, Elastic wave velocities in heterogeneous and porous media, *Geophysics*, 21,1, 41-70 (1956)