

4



Tying surface seismic data

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4.1 Introduction

Conventionally, surface seismic surveys provide sub-surface images in time in two or three dimensions (2D or 3D). Well measurements are data obtained as a function of depth. VSP-type well seismic surveys provide both time images (VSP sections) comparable to those obtained by surface seismic surveys, and surveys (velocity for example) in depth, comparable to those obtained by logging measurements (for example, acoustic logging). The comparison of measurements in depth (acoustic logging) and measurements in time requires time or depth conversion of one of the two datasets.

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Acoustics is the most natural link between geophysics and logging. Although functioning in very different frequency bands (a few tens of kHz for acoustic logging and a few tens to a few hundred Hz for Very High Resolution (VHR) seismic surveys), acoustic and seismic well measurements are governed by the same laws of wave propagation.

This chapter shows:

- the principle of depth conversion of surface seismic methods using VSP data (Vertical Seismic Profile, Chapter 2);
- the influence of cementation on acoustic measurements;
- the principle of the calibration of formation velocity measurements obtained by acoustic logging with those provided by VSP;
- the principle of time conversion of acoustic data (acoustic logging, Chapter 3) and the calculation of synthetic seismograms;

The data used in this chapter are near surface data derived from a 3D VHR seismic survey, a vertical seismic profile, and a full waveform acoustic log.

4.2 3D VHR seismic survey and VSP

The acquisition device is composed of a receiving device and a transmitting device. The receiving device, stationary during acquisition, is composed of 2 parallel lines of 24 geophones, spaced 2 m apart. The distance between the 2 geophone lines is 4 m. The device consists of 11 source lines, oriented perpendicular to the geophone lines (in-line direction) with 11 shots fired per line. The distance between 2 shots on a line is 2 m. The distance between 2 source lines is 4 m. The direction of the source lines is cross-line. There is no overlap between transmitting and receiving devices. The distance between the 2 devices is 4 m. The source used is a weight drop (Chapter 2, Figure 2.5).

Seismic data processing provided a 3D block of 13 in-line sections spaced 1 m apart (Mari and Herold, 2015). Each section is composed of 44 Common Mid-Point gathers (CMP) 1 m apart. The listening time has been limited to 250 ms, the time sampling step is 0.5 ms. Figure 4.1 shows the seismic acquisition device (left) and an example of in-line and cross-line seismic sections derived from the 3D block (right). The two sections presented (section 6 in the in-line direction, and section 23 in the cross-line direction) intersect in the middle of the 3D block. They have been filtered in the 15-150 Hz bandwidth, which provides an excellent signal-to-noise ratio. The CMP point located at the intersection of the in-line seismic section 3 and cross-line 6 is located about twenty meters from a borehole in which a VSP has been recorded.

VSP data is used to tie surface seismic data. The VSP in this case is a near surface VSP, recorded in a steel cased vertical well.

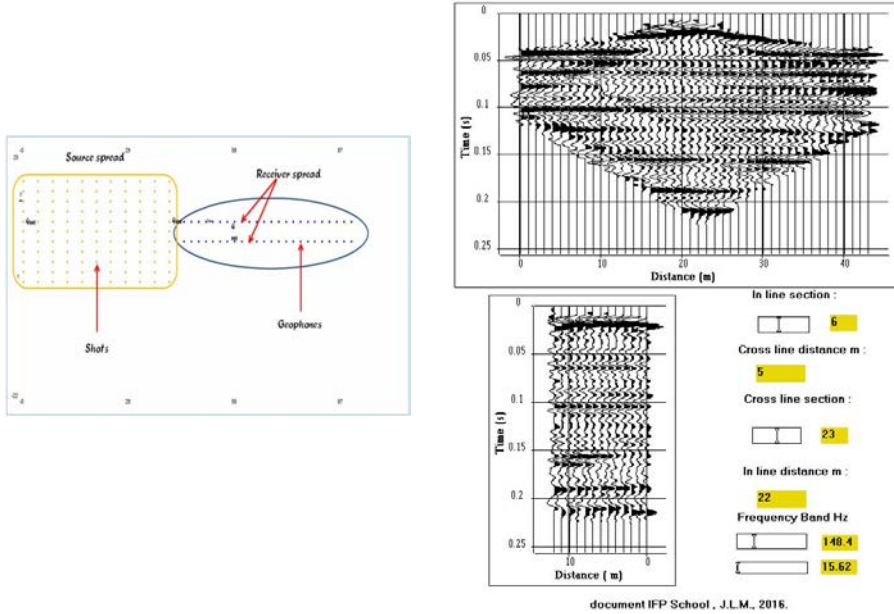


Figure 4.1 3D seismic survey; left: acquisition device, right: time sections.

The acquisition and processing sequence are described in Chapter 2 and the processing results are presented in Figures 2.11 and 2.12. It should be noted that the depth of the receiver varies between 25 and 85 m, the surface source being slightly offset (5 m) relative to the wellhead. There is a 5 m distance between two successive positions of the geophone in the well.

Figure 4.2 shows:

- Top left: unprocessed VSP recording;
- Top right: the vertical time-depth relationship and the interval velocity law at the seismic sampling interval in depth, i.e. 5 m;
- Bottom left: the stacking corridor of the VSP section and the VSP stacked trace;
- Bottom right: Tying of the seismic section on the VSP stacked trace at the intersection of the in-line 3 and cross-line 6 seismic sections.

The VSP stacked trace, duplicated 5 times, is inserted in the in-line section 3 at the CMP position associated with the cross-line section 6. The correlation coefficient between the seismic trace and the VSP corridor trace at the point of intersection is greater than 0.72, thus showing a good time fit of the seismic horizons. However, slight differences between the amplitudes observed on the surface seismic and the VSP stacked trace can be noted. This difference is due to the choice of amplitude compensation laws used for the two data sets. For surface seismic, an AGC-type

gain law on a short window (30 ms) was used to highlight the reflectors close to the surface, which had the effect of increasing the amplitude of the reflectors.

It can be noted that the VSP allows a calibration of the surface seismic in the depth range (25 to 85 m) where the measurements were made, but also under the well. The VSP stacked trace highlights reflectors that appear at times (two way times) greater than 80 ms and are below the well. Seismic reflectors can be seen beyond 100 ms.

This example illustrates the predictive role of VSP: prediction under the well.

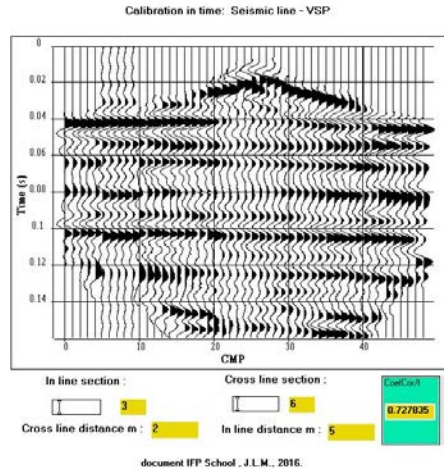
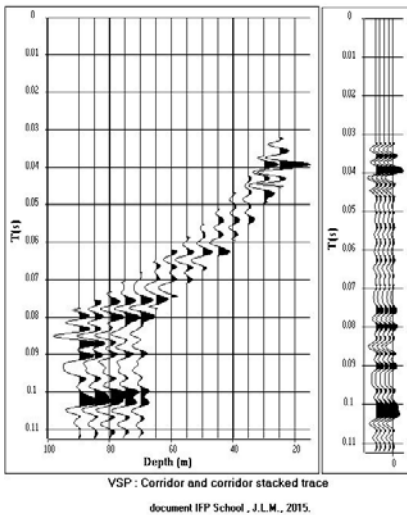
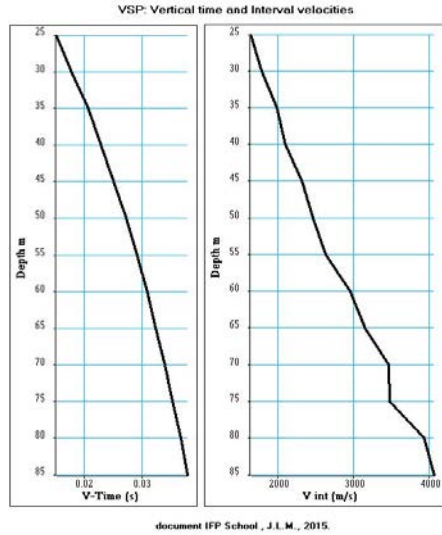
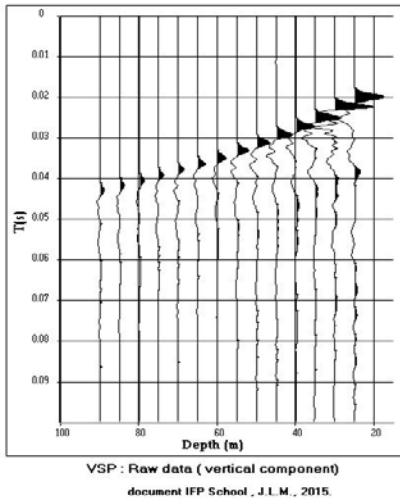


Figure 4.2 Tying a seismic section using VSP.

The time-depth law $T = f(Z)$ can be used to convert time seismic sections into depth seismic sections. The procedure can be summarized as follows:

- The vertical times T measured on the VSP must be transformed into vertical two way times TWT as a function of the depth Z : $TWT = f(Z)$.
- Law $TWT = f(Z)$ must be inverted $Z = f^{-1}(TWT)$
- Law $Z = f^{-1}(TWT)$ should be sampled with a depth sampling rate Δz : $Z = f^{-1}(TWT, \Delta z)$. The sampling rate Δz must be chosen to avoid aliasing phenomena between the time to depth conversion procedure.
- The conversion is done by vertical translation between a time position TWT and a depth position Z . The horizons will not be moved laterally on the sections. As a result, if there are dips, the time sections must be migrated before depth conversion.

Figure 4.3 shows the conversion in depth of the seismic time sections from Figures 4.1 and 4.2.

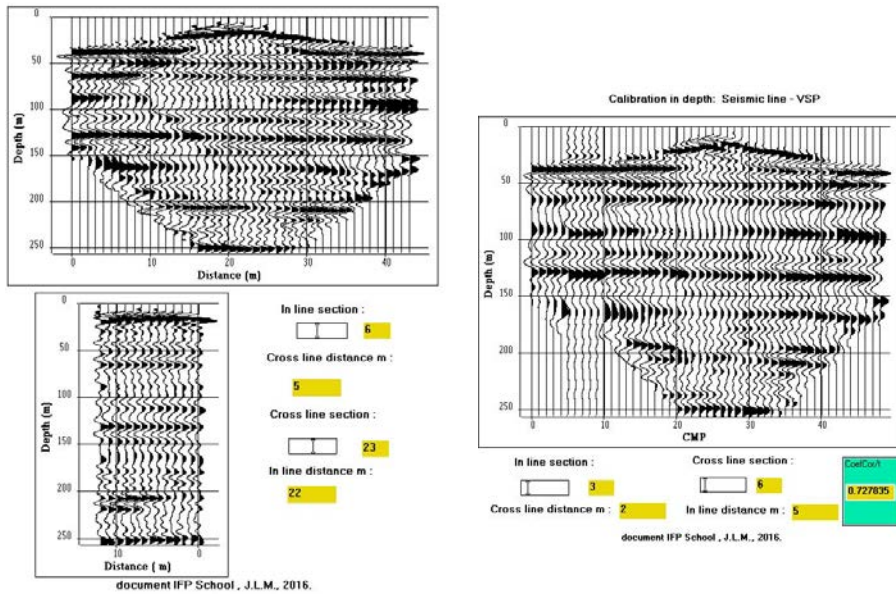


Figure 4.3 3D seismic in depth.

Reflectors can be seen down to 250 m deep. Figure 4.3, right, shows the tying in depth by VSP stacked trace of the in-line seismic section 3 at the intersection with the cross-line seismic section 6.

4.3 Acoustic logging

A full waveform acoustic log (Chapter 3) was recorded in the borehole. The borehole is steel cased and poorly cemented. The acoustic tool (see Chapter 3, Figure 3.1 left) is a monopole type flexible tool with a small diameter (50 mm) used in its wide configuration, with a far transmitter-receiver distance (3 to 3.25 m). 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 4.4 shows the 2 acoustic sections.

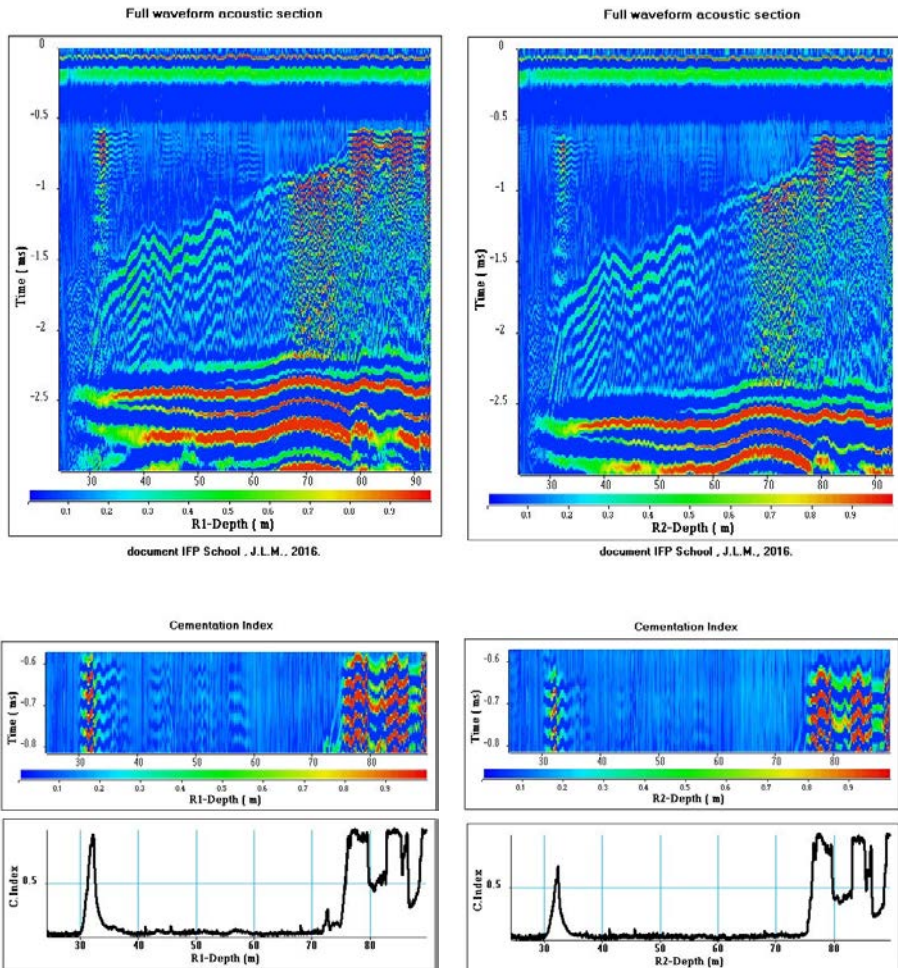


Figure 4.4 Acoustic sections and cementation logs.

The acoustic sections show:

- 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.
- 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 high amplitude waves, guided by the borehole wall, appear after 2.4 ms. They are influenced by casing.

The lower part of Figure 4.4 shows the acoustic sections in the time interval 0.6 to 0.8 ms where the resonances are mainly 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, referred to here as C index (cementation index). The C index indicates areas of poor cementation, especially in the 30 to 35 m range and at depths greater than 75 m.

4.4 Acoustic logs

Acoustic logging is mainly used to provide formation velocities by measuring the arrival time difference of the different wave trains at the different receivers of the tool, in this case R1 and R2 at 3 m and 3.25 m respectively from the acoustic source. Figure 4.5 shows the following logs for refracted P-waves:

- The P-wave velocity log (V_p) calculated from the time difference δt between the acoustic signals observed on the receivers R1 and R2
- The correlation log between the acoustic signals observed on the receivers R1 and R2, after compensation for δt . A high value of the correlation coefficient indicates a strong similarity between the two signals and a good velocity measurement. In this example, the correlation coefficient is greater than 0.75 for more than 70 % of the measured velocities. It is used to edit the log.
- P-wave velocity log after editing
- The instantaneous frequency log, which clearly shows the change in the frequency content of the acoustic signal at 65 m.

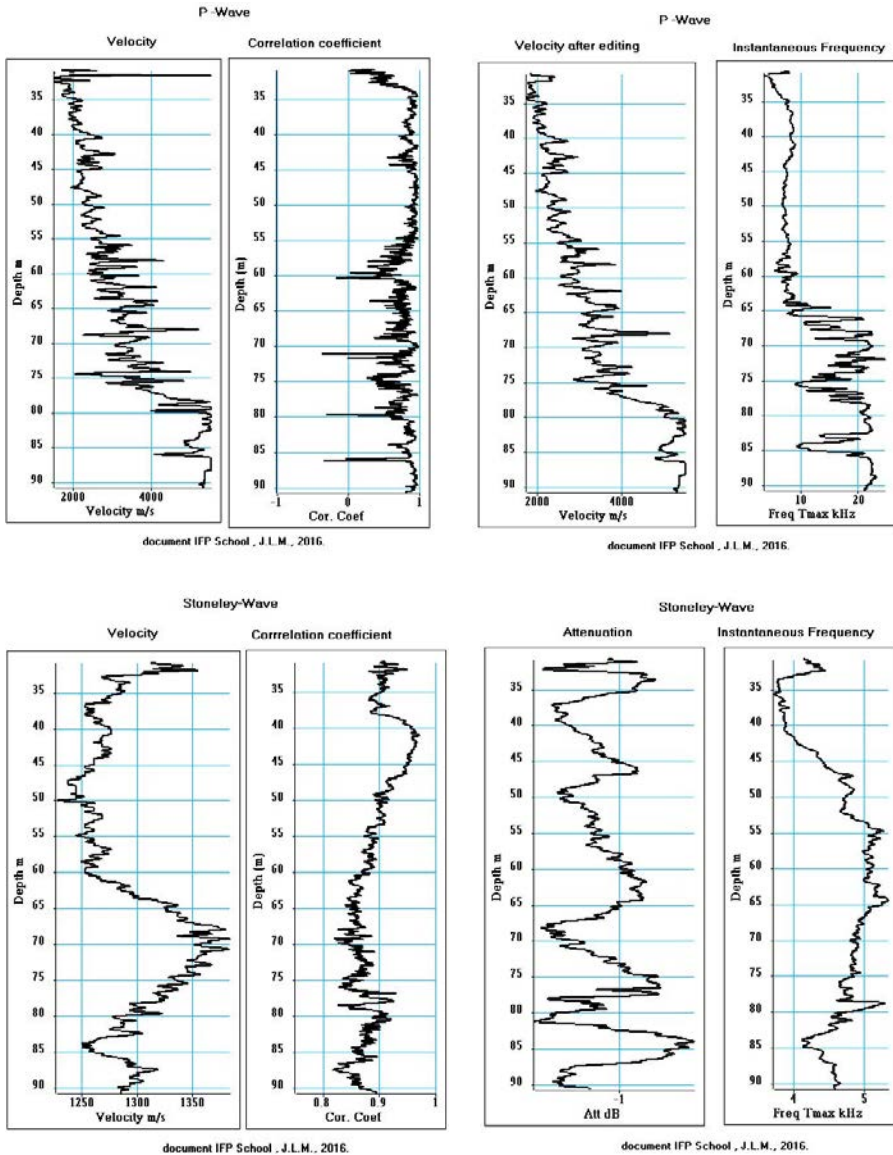


Figure 4.5 Acoustic Logs: P-waves and Stoneley waves.

The lower part of Figure 4.5 shows the acoustic logs associated with the Stoneley waves:

- The velocity log and its associated correlation coefficient log. The very high values of the correlation coefficient (> 0.8) indicate that the measured velocity values are accurate.

- The attenuation log that shows that these waves are barely attenuated. These waves are sensitive to the borehole wall conditions and therefore to the presence of casing. It is worth using the information provided by the Stoneley waves in an open hole to characterize the geological formation and in particular to detect the presence of fractures.
- The frequency log. These waves are dispersive and low frequency (between 4 and 5 kHz).

4.5 Time conversion of acoustic logs and calculation of the synthetic seismogram

The velocity log is a measurement made according to depth, sampled at regular intervals (2 cm in this case). It can be used to obtain a time-depth law by integrating the acoustic transit time as a function of depth. At a given depth, the acoustic transit time is equal to the depth sampling interval divided by the formation velocity. The integration of the acoustic transit time provides the integrated time, conventionally known as the Integrated Transit Time (ITT(Z)). If the borehole is vertical, the ITT can be compared to the vertical time provided by the VSP.

The integrated transit time $ITT(Z) = f(Z)$ can be used to convert a depth log into time log and to insert these logs on the seismic sections in time. For this purpose, ITT(Z) must be set in two-way time. The depth-time conversion of the log will be done by vertical translation between a position Z in depth, and a time position ITT(Z) with a regular time sampling interval Δt : $ITT(Z) = f(Z, \Delta t)$. The sampling interval Δt must be chosen to avoid aliasing phenomena between the depth domain and the time domain. Δt must be chosen as a sub-multiple of the seismic sampling interval, to change the scale between the logging measurements and the seismic measurements.

Figure 4.6 (a and b) shows the time conversion of velocity and cementation logs measured in depth. The velocity log is used to calculate a reflectivity log (Figure 4.6c) that was filtered in terms of frequency and under-sampled at 0.5 ms (seismic sampling interval in time).

On the filtered reflectivity log, a high amplitude reflector can be seen at around 70 ms.

The filtered reflectivity log is known as the synthetic seismogram. It is used as the VSP stacked trace to calibrate the seismic horizons observed on seismic sections in time. The synthetic seismogram, duplicated 5 times, is inserted into the in-line section 3 at the CMP position associated with cross-line section 6 (Figure 4.6d). It can be noted that the 70 ms horizon is not present on the seismic section or on the VSP stacked trace (Figure 4.2). At 70 ms, the velocity log increases abruptly. This phenomenon occurs where poor cementation is detected (Figure 4.6b). The presence of the horizon at 70 ms is an artifact related to a velocity anomaly due to the

poor cementation between the casing and the formation. The measured acoustic velocity represents the formation velocity for times under 70 ms. However, the correlation coefficient between the seismic trace and the synthetic seismogram at the intersection point is greater than 0.7, showing a good tying of the seismic horizons in the time interval 38-60 ms. It falls to 0.5 if we consider the interval 38-80 ms.

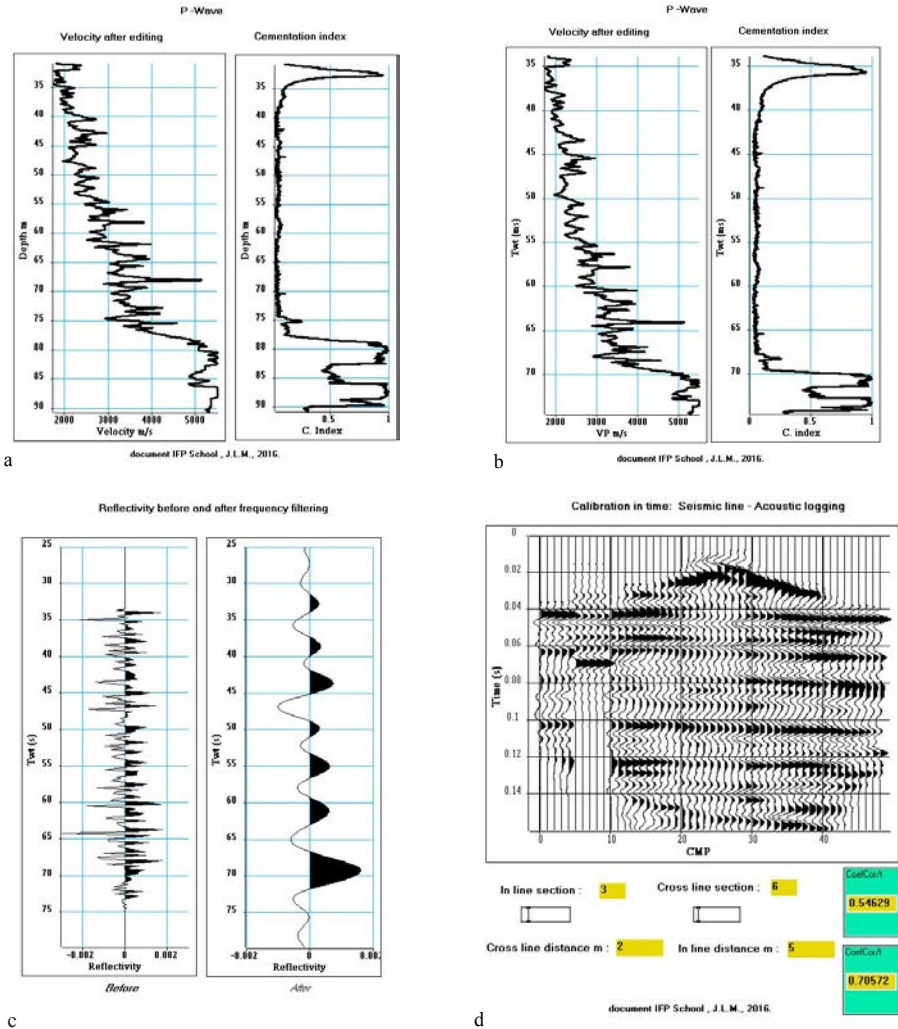


Figure 4.6 Seismic section and synthetic seismogram before "block shift"; a: velocity log and cementation log in depth; b: velocity log and cementation log in time; c: reflectivity before and after frequency filtering; d: raw tying in time of the seismic section with frequency filtered reflectivity.

4.6 Integrated sonic time and VSP vertical time

Figure 4.7 shows a comparison between the integrated sonic time and the VSP vertical time. The times are set to 0, at 30 m deep, a depth from which the acoustic measurement can be made. In this acquisition the water level was detected at 30 m. It can be seen that the two-time curves are superimposable in the 30 to 77 m range. From 77 m, sonic times are shorter than the VSP times. The drift curve, which is the difference between the sonic times and the VSP times, clearly shows this phenomenon. To reconcile sonic and VSP times, the acoustic velocities must be modified so that the recalculated integrated sonic times are closer to the measured VSP vertical times.

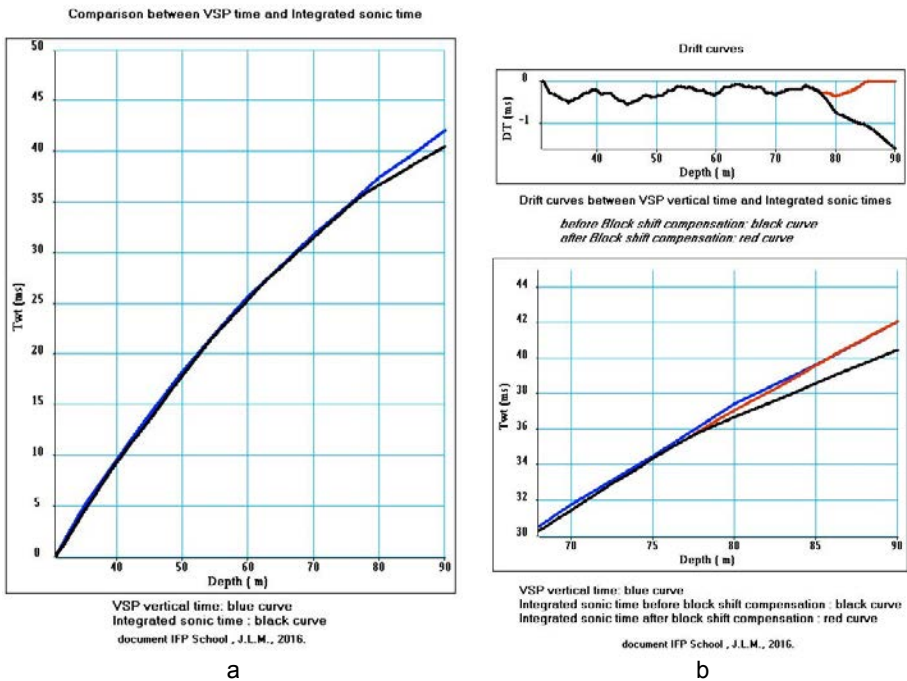


Figure 4.7 VSP time and integrated sonic time - block shift method; a: comparison of VSP times and integrated sonic times; b top: drift curves before and after velocity compensation by the "block shift" method; b bottom: comparison of VSP and integrated sonic times before and after velocity compensation using the "block shift" method.

This procedure cannot guarantee that the acoustic velocities thus corrected are the exact velocities of the formations.

Acoustic velocity anomalies have several origins:

- measurement-related anomalies: noise and cycle skipping for picking based on the threshold, stretching (difficult to detect),
- anomalies linked to formations: poor cohesion between grains (measured velocity too low), vacuoles (measured velocity too high),
- anomalies related to the wave path: invasion, cavities, mud paths (in the case of large diameter holes), alteration of the borehole wall,
- anomalies due to poor cementation (as in the example shown here).

The refracted acoustic wave can propagate in the washed or invaded zone of the formation due to the invasion phenomenon and not in the virgin zone. The seismic wave (VSP) emitted at the surface, propagates mainly in the virgin formation. To obtain acoustic velocities in the virgin zone, it is necessary to correct or tie the acoustic velocity log with propagation time measurements in the virgin zone obtained from the VSP picked times. For this purpose, the drift curve is used to determine the values of velocity correction to apply to the measured acoustic velocities so that the new integrated times are closest to the VSP vertical times. The drift curve can be approximated by straight line segments. A velocity correction value will be calculated for each line segment. In the example presented here, the drift curve can be approximated by 2 straight-line segments, the first in the 30 to 77 m depth range, the second in the 77 to 90 m depth range. In the first interval, we note that the time difference is constant on average (0.5 ms). This value corresponds to the precision of the picking. As a result, the sonic velocity curve will not be modified in this depth range. In the 77 to 90 m range, the drift curve has a significant gradient that can be compensated for by a constant velocity correction value. The correction method is known as a “block shift” (Boyer and Mari, 1997). Figure 4.7b, top, shows the drift curve before and after “block shift” compensation, and, bottom, the comparison of the VSP times and the integrated sonic times before and after “block shift” compensation. Figure 4.8 (a and b) shows, in depth and time, the velocity logs after “block shift” correction and the cementation logs. The corrected velocity log was used to calculate a reflectivity log (Figure 4.8c) that was filtered in terms of frequency and under-sampled at 0.5 ms.

On the filtered reflectivity log, we can see that the high amplitude reflector of around 70 ms has disappeared. The reflectivity log was inserted into the seismic section and the correlation coefficient between the reflectivity log and the seismic trace at the well was measured at 0.77, thus confirming a good tie of the seismic horizons in time.

This example shows that synthetic seismograms can be used to tie seismic sections, after the acoustic velocity logs have been validated on measurements of vertical time obtained by VSP.

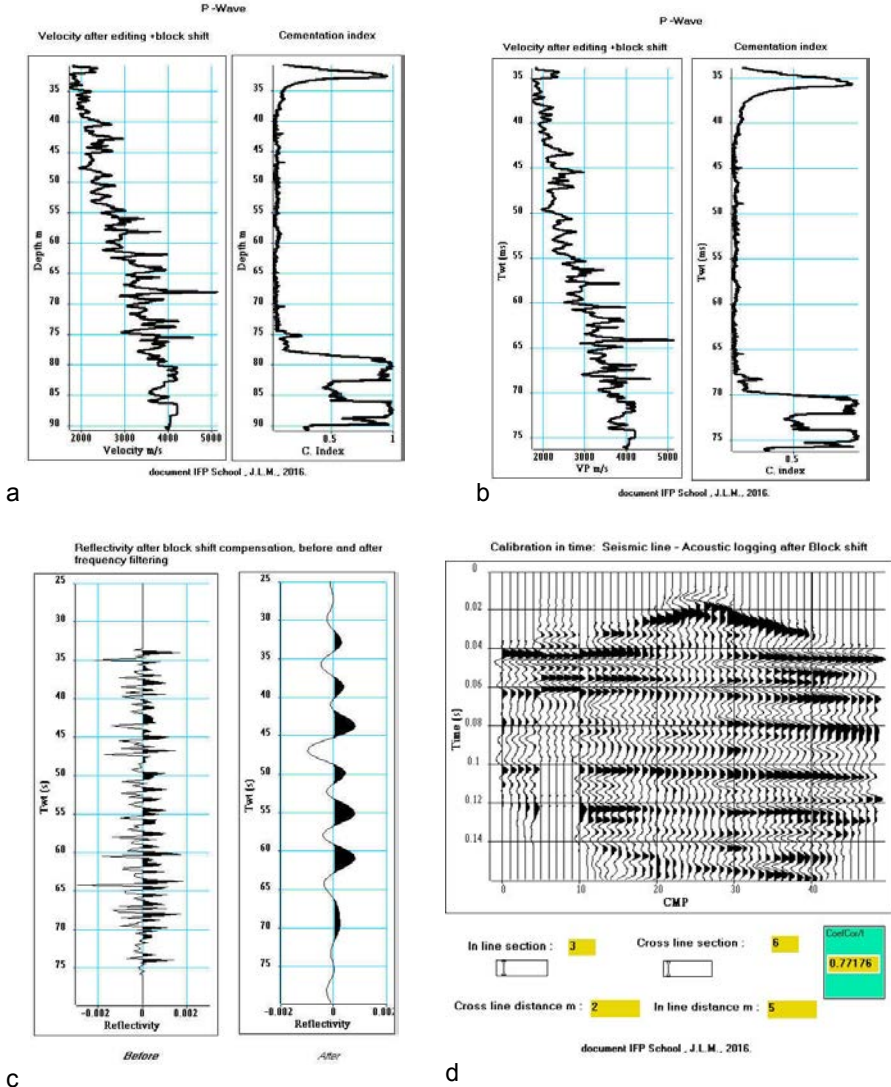


Figure 4.8 Seismic section and synthetic seismogram after block shift; a: velocity log and cementation log in depth; b: velocity log and cementation log in time; c: reflectivity before and after frequency filtering; d: raw tying in time of the seismic section with reflectivity filtered in terms of frequency.

4.7 Conclusion

This example presents the use of VSP and acoustic logging for tying surface seismic sections. Figure 4.9 shows the comparison between tying the section using acoustic logging (synthetic seismogram) and the use of VSP stacked trace. The synthetic seismic traces and the VSP stacked trace are inserted into the in-line seismic section 3 at the intersection with the cross-line seismic section 6. The synthetic seismogram enables the reflectors to be tied in the depth range where the logs have been recorded. The VSP stacked trace allows the tying in the same depth range, but it also enables the prediction of reflectors under the well, particularly in the 90 to 140 m range.

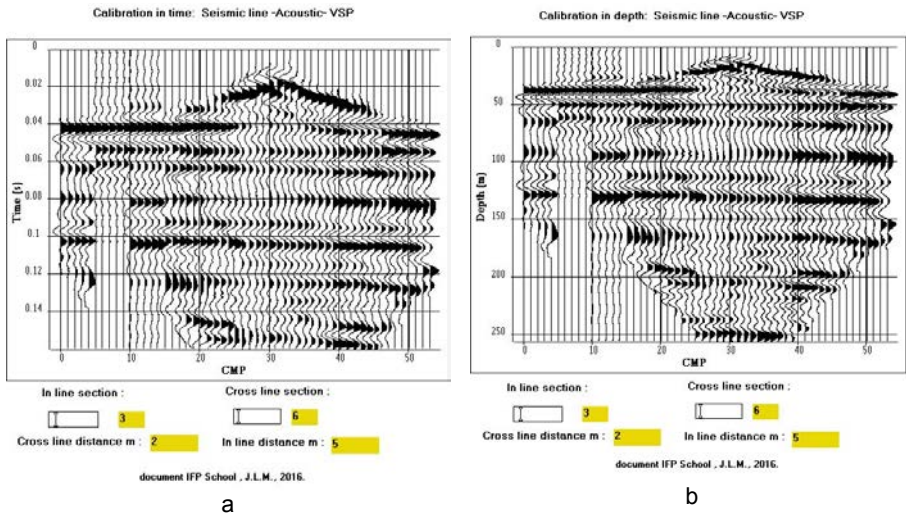


Figure 4.9 Tying of a seismic section using a VSP and an acoustic log; a: in time, b: in depth.

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