# 2

# Well seismic surveying

J.-L. Mari, C. Vergniault, F. Coppens

## 2.1 Introduction

Well seismic surveying, the most commonly used form of which is Vertical Seismic Profile or VSP (Hardage 1985, 1992; Mari et al., 1999, 2003), is a seismic method involving a signal that is emitted on the ground surface, which is then recorded by a seismic receiver located at various depths in the well. The earliest type of well seismic measurement is the check shot survey, which is used to measure propagation times between the surface and various well depths.

VSP is a well seismic method for which the source and the receiver are considered to be on the same vertical. The VSP vertical resolution ranges from meters to tens of meters and its lateral range of investigation can reach a few tens of meters (Fresnel zone).

VSP is based on the analysis of different wave trains recorded by the well receiver. The measurement of the arrival time of the first downgoing waves that propagate close to the near-normal incidence is used to provide a velocity distribution in the

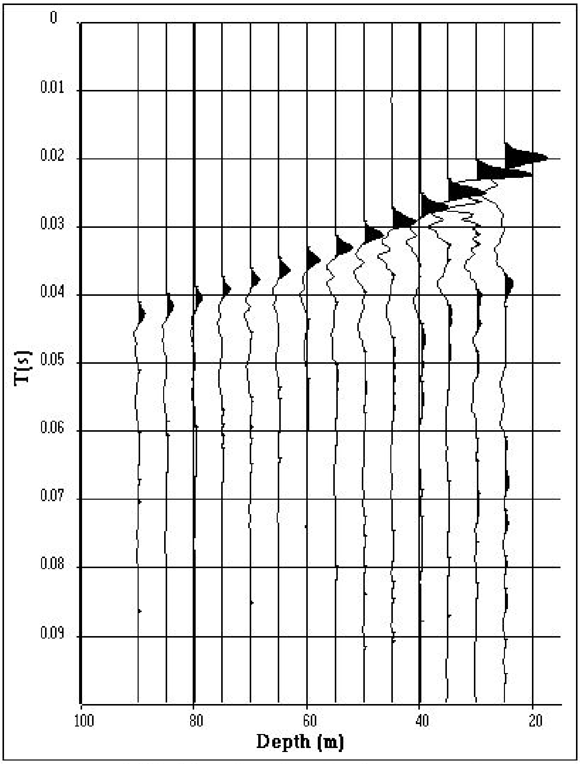
---

DOI: 10.1051/978-2-7598-2263-8.c004

subsurface. After processing, the VSP provides a seismic trace without multiples, which is directly comparable to a surface seismic section recorded in the vicinity of the well. With the added constraints of log data (sonic and density), this trace represents an acoustic impedance log in the well and below the bottom of the well.

The well may be an open hole, a cased hole (steel and/or PVC) or a cemented cased hole. For the latter, a cementation control (acoustic logging) is recommended.

Figure 2.1 shows an unprocessed VSP recording of a steel-cased vertical well. In this representation, the horizontal axis shows the various depths of the well geophone, and the vertical axis represents listening time. In this example the receiver depth varies between 25 and 90 m, and the surface source is slightly offset (5 m) with respect to the wellhead. The distance between two successive geophone positions in the well is 5 m. The sampling rate in time is 0.25 ms for a listening duration of 250 ms. In the Figure, the listening time has been limited to 100 ms.



VSP : Raw data ( vertical component)

document IFP School , J.L.M., 2015.

Figure 2.1 *Example of VSP recorded in a vertical well at depths of between 25 to 90 m.*

The lateral range of investigation of the VSP can be improved by offsetting the source with respect to the well. This technique is called Offset Vertical Seismic Profiling (OVSP). The image obtained after processing is thus a single-fold seismic section.

A Seismic Walkaway is a series of offset VSPs, with the surface source situated at several locations corresponding to successively increasing offsets with respect to the borehole. The image obtained after processing is a section with a low degree of multiple fold coverage. In this type of setup, the number of positions of the well geophone is generally limited. Figure 2.2 illustrates the implementation of a seismic walkaway and shows an example of the type of imagery obtained in the oil industry. The horizontal axis represents the distance of the mirror point with respect to the well.

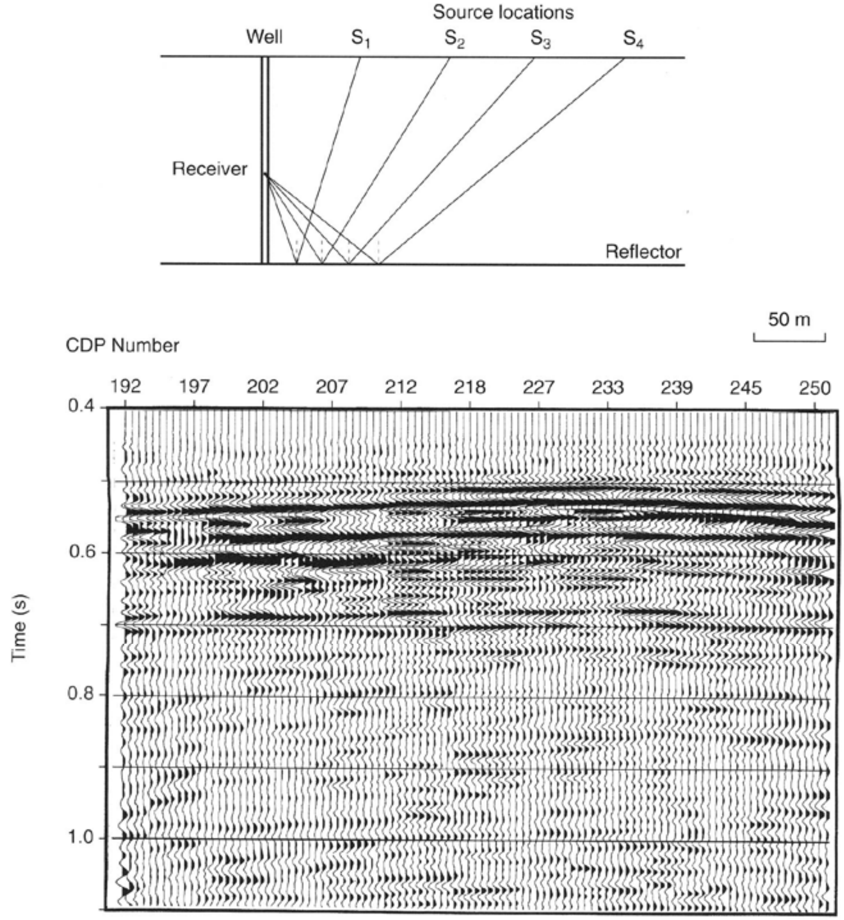


Figure 2.2 *Example of imaging with seismic walkaway (document: ENGIE - IFPEN).*

However, the lateral range of investigation of a seismic walkaway is limited (to between several hundred meters up to a kilometer) compared to that of a classic seismic reflection profile. This underlines the local nature of a reservoir study using a well seismic method.

VSP, OVSP and seismic walkaway implementations provide an image of the geological formations below the well. During drilling, the drill bit itself can be used as a well source, thereby permitting the imaging of formations that have not yet been reached while the well is being drilled (prediction ahead of the bit).

The use of a well source enables reverse well seismic surveys (source at the bottom and receiver on the surface) to be carried out, along with well-to-well seismic surveys. This aspect has been developed in Chapter 1, which focuses on the measurement of formation shear velocities. Well-to-well seismic surveying can provide images of formations between wells in the form of seismic reflection sections, which give acoustic impedance contrasts (Figure 2.3 - left) or velocity models obtained by inversion of first arrival times (tomography by transmission, Figure 2.3 - right).

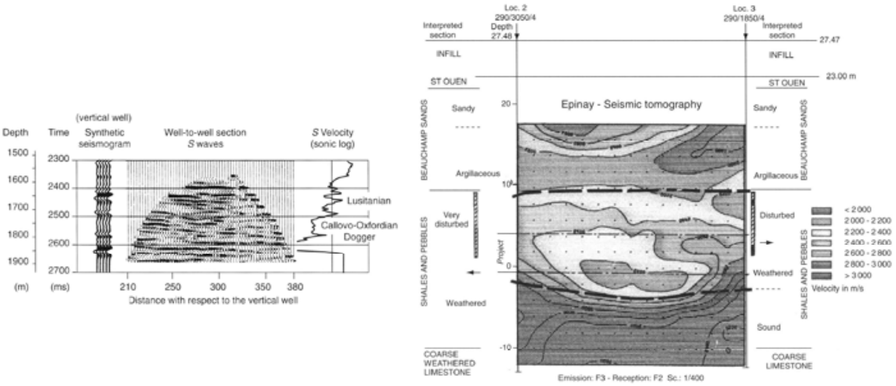


**Figure 2.3** *Examples of well-to-well seismic surveying. Left: example of well-to-well seismic measurement – reflection of S-waves between a vertical well and a deviated well (from Becquey et al., 1992). Right: Example of transmission tomography in civil engineering (F. Lantier, consultant)*

The various implementations of well seismic methods can be grouped under the general term of well seismic profiling.

## 2.2 Well seismic data acquisition

Typically, well seismic profiling is carried out with a seismic source at the surface and a receiver system in the well. In this paragraph, we present:

- the necessary resources for data acquisition;
- implementation in the field.

### 2.2.1 *Necessary resources for data acquisition*

We present here a list of the necessary resources, in terms of: equipment, vehicles and personnel.

- **Equipment**
  1. logging unit, which includes:

     a receiver system composed of one or more well sensors (geophones and/or hydrophones), a winch with several hundred meters of cable, that is connected to the well sensor, 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 surface sensors for source calibration;
  3. a seismic source (explosive, hammer, weight drop);
  4. a lifting system with pulleys to lower the receiving system;
  5. equipment should be checked (maintenance, calibration) periodically.
- **Vehicles**
  1. either: 1 or 2 vehicles (preferably all-terrain/off-road), enabling the transport of personnel and equipment
  2. or: one logging unit and one vehicle to transport personnel and the source.
- **Personnel and expertise**
  1. two operators qualified for the implementation (source, winch, acquisition);
  2. one geophysicist (Head of Mission) qualified for data quality control at acquisition and who can also be an operator.

### 2.2.2 *Implementation in the field*

In this section, we describe:

#### 2.2.2.1 Description of classical VSP operation in a vertical well

The well receiver or probe is lowered to a certain depth. The source is positioned on the ground surface at a short distance (<5 m) from the wellhead. A reference geophone is sited near the wellhead. Several seismic shots are carried out to verify the proper functioning of the entire acquisition system (recorder, probe, reference geophone, source) and good data repeatability. The probe is then raised to the surface.

After setting the zero (probe reference) according to a reference plane (raft, rotary table...) or on the ground surface, the probe is lowered to the bottom of the well and anchored to the well wall. Prior to this step, it is important to verify that the probe anchorage is sufficient to make measurements with the loose cable.

The VSP operation at a given depth involves:

1. Checking the depth of the well receiver or probe,
2. Anchoring the probe (if the probe type allows the anchor arms to be opened and closed),
3. Slackening the cable,
4. Recording seismic data and checking them using the visualization system,
5. Verifying the repeatability of the source on the seismic channel dedicated to the reference geophone,
6. Tightening the cable,
7. Unattaching the probe (if the probe type allows the anchor arms to be opened and closed),
8. Positioning the probe at the next depth.

This procedure can be repeated several times at the same depth to evaluate the variations in coupling and the signal-to-noise ratio.

Well seismic operations can be carried out in vertical, deviated or horizontal wells, in open or cased holes.

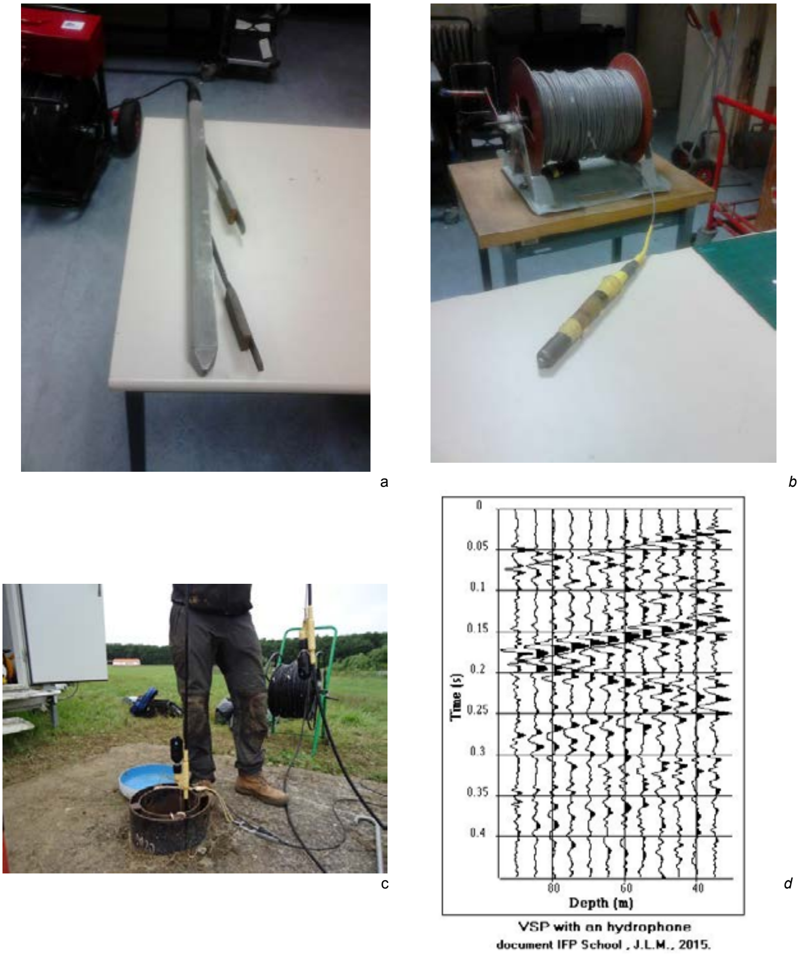
#### 2.2.2.2 Well probes

- In the petroleum industry, most receiver systems are multi-sensor probes for the purpose of reducing well seismic data acquisition time and thus the costs of well downtime. These systems are array probes that include a master unit and satellite tools. They allow simultaneous recording at several depths and are particularly useful for seismic walkaway operations. The master tool includes a telemetry system that transfers data from the bottom to the surface. Each tool includes an anchoring system and a seismic module. In geotechnics, the drilling probe is usually a single-sensor probe.
- The receiver can be a single-component geophone (vertical geophone) or a three-component geophone (a vertical component and two orthogonal horizontal components). The receiver can also be a hydrophone, or even have four components: a three-component geophone and a hydrophone. In geotechnics, a geophone-type single-sensor probe with 1 or 3 components is conventionally used. The anchoring system can be hydraulic or mechanical, with or without

anchor arms that open and close. In geotechnics, a single hydrophone or hydrophone array (12 levels, for example) can also be used.

- If the anchoring system allows the anchor arms to be opened and closed, it is recommended to make seismic measurements at several depths while descending and to make measurements at the same depths when ascending, to control depth tying.
- VSP acquisition is carried out from the bottom of the well towards the surface for reasons of data acquisition convenience.

Figure 2.4 shows some well probe types: a 3-component geophone, a single hydrophone, and a hydrophone array. The figure also shows an example of a VSP obtained with a hydrophone.



VSP with an hydrophone
document IFP School , J.L.M., 2015.

**Figure 2.4** *Examples of well probes (a: 3C geophone, b: hydrophone, c: hydrophone array, d: example of VSP recorded with a hydrophone).*

### 2.2.2.3 Seismic source

The seismic source must be the appropriate size for an optimal Signal/Noise ratio for the investigated well depth and for a suitable frequency content. The most used sources are: explosive (high energy but can cause a nuisance and authorization is limiting), gun (cartridge), hammer (practical but low energy) and weight drop (good compromise energy/bulk). These sources emit mainly compression-type volume waves. You can also use a mini-vibrator. The petroleum industry generally uses the seismic source for surface seismic data acquisition (vibrator). In water, an air gun is normally used. To emit S-waves, a hammer can be used to laterally strike a target anchored to the ground. This point is developed in Chapter 1.

Figure 2.5 shows examples of seismic sources used in civil engineering.

*Source: gun*

*Source: Weight drop (APEC document)*

Figure 2.5 *Seismic sources used in civil engineering.*

### 2.2.2.4 Acquisition parameters

The VSP recording is a two-dimensional recording (time: vertical axis; depth or length: horizontal axis). The sampling interval is 0.25 ms, 0.5 ms or 1 ms. The listening time ranges from a few hundred ms to a few seconds. The vertical distance $\Delta z$ between 2 measurement points (sampling according to depth, i.e. the horizontal axis) must be chosen to be less than the smallest half-wavelength encountered to avoid spatial aliasing phenomenon. $\Delta z$ is calculated from the lowest propagation velocity $V_{min}$ of the seismic waves and the highest frequency $F_{max}$ likely to be recorded: $\Delta z \leq V_{min}/2F_{max}$. If $V_{min} = 1500$ m/s and $F_{max} = 150$ Hz, we will choose $\Delta z \leq 5$ m.

In practice, vertical distances of between 2 m and 5 m are chosen in geotechnical engineering. For a seismic walkaway acquisition, the offset D of the source relative to the wellhead depends on the depth H of the objective. For reflection imaging, the angles of incidence should not exceed 30 degrees. As a rule of thumb, D < 3/4 H.

#### 2.2.2.5 Security

Site security must be ensured by the Head of Mission, in accordance with the Quality System of the provider. Access to the measurement area must be secured. Only professionally qualified personnel are permitted to use explosives.

#### 2.2.2.6 Quality Control

At each depth interval, the operator controls the quality of the recordings (well and surface receiver, noise level, good coupling of the well receiver…).

#### 2.2.2.7 Production

On average, for a standard VSP: 5 mn/depth.

## 2.3 Seismic waves

The VSP recording is composed of downgoing and upgoing P and/or S volume waves as well as of interface/guided waves related to the presence of the well and the well fluid. Guided waves are Stoneley waves, more commonly known as tube waves.

The downgoing volume waves are direct waves emitted by the source. They result in direct arrivals and all the multiple events created by seismic markers located above the well receiver. Upgoing volume waves are primary and multiple reflected waves.

Downgoing waves have positive apparent velocities, upgoing waves have negative apparent velocities.

Tube waves are created when the particles of the sludge column that fills the well are set in motion. Surface waves are the main source of tube waves, which are considered as organized noises that disrupt VSP recordings and interfere with interpretation. There are, however, tube waves that may be useful to the geophysicist. These are the tube waves created in situ in areas of high permeability via compression waves that cross the permeable zone and give rise to two tube waves, one upgoing, the other downgoing as shown in Figure 2.6. The amplitude of these two tube waves is directly proportional to the permeability of the area where they were created and the value of the permeability thus found is significant compared to the well over a distance equal to the dominant half-length of the incident compression wave (Huang and Hunter, 1981). An example of tube wave analysis in a reservoir zone is presented by J.L. Mari (1989).

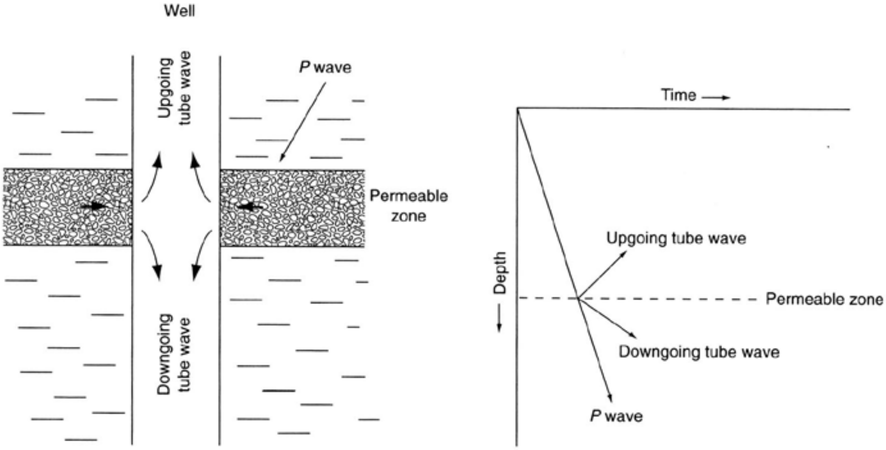


Figure 2.6 *Creation of tube waves by compressional waves crossing a permeable zone, and schematic representation of these waves on the VSP record (from Hardage, 1985).*

Figure 2.7 shows a VSP with a high level of tube waves, labeled TW1 to TW6. We can identify the direct downgoing wave (first arrival), a set of upgoing reflected arrivals intersecting the direct arrival and some downgoing and upgoing tube waves. The surface waves generated by the source create a field of tube waves (TW3) that is reflected at the well bottom (TW4), and at the top of a porous and permeable zone located at a depth of 440 m (TW5). TW5 is reflected again at the surface on the fluid-air contact (TW6). The downgoing P-wave that enters the permeable zone at 440 m creates a tube wave (TW1) that is reflected at the well bottom (TW2). Secondary tube waves with a low apparent velocity can be noted, due to the tool itself. Stoneley waves can also be used to obtain information on the shear wave velocity of the formation, and to detect fracture zones and karsts. An example of the use of tube waves to detect karstic levels of a near-surface carbonate reservoir is presented in Chapter 5. In this case, it is preferable to use a hydrophone as a seismic sensor.

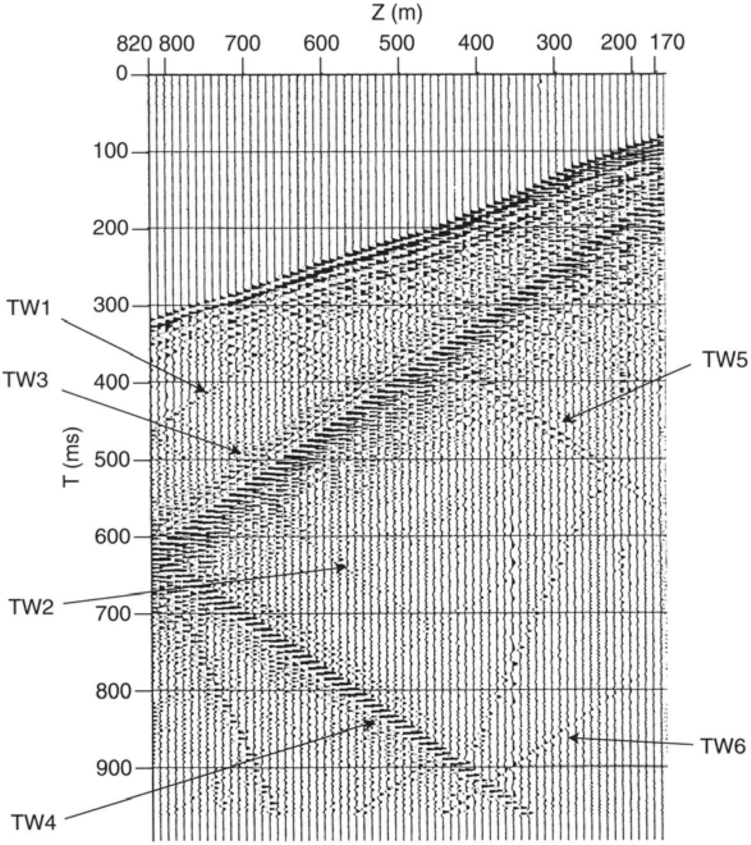


Figure 2.7 *Example of VSP with tube waves (ENGIE – IFPEN).*

When the source is offset, we can observe conversion phenomena. To properly understand the wave propagation it is necessary to record data with multi-component receivers. Figure 2.8 shows an offset VSP recorded with a two-component well geophone, vertical component Z and horizontal component H.

For both components the first arrival is the direct P-wave. We can observe a downgoing S-wave with a low apparent velocity that is more visible on the horizontal component. Upgoing waves are visible on both components, the apparent velocity of S-waves being lower than that of the P-waves.

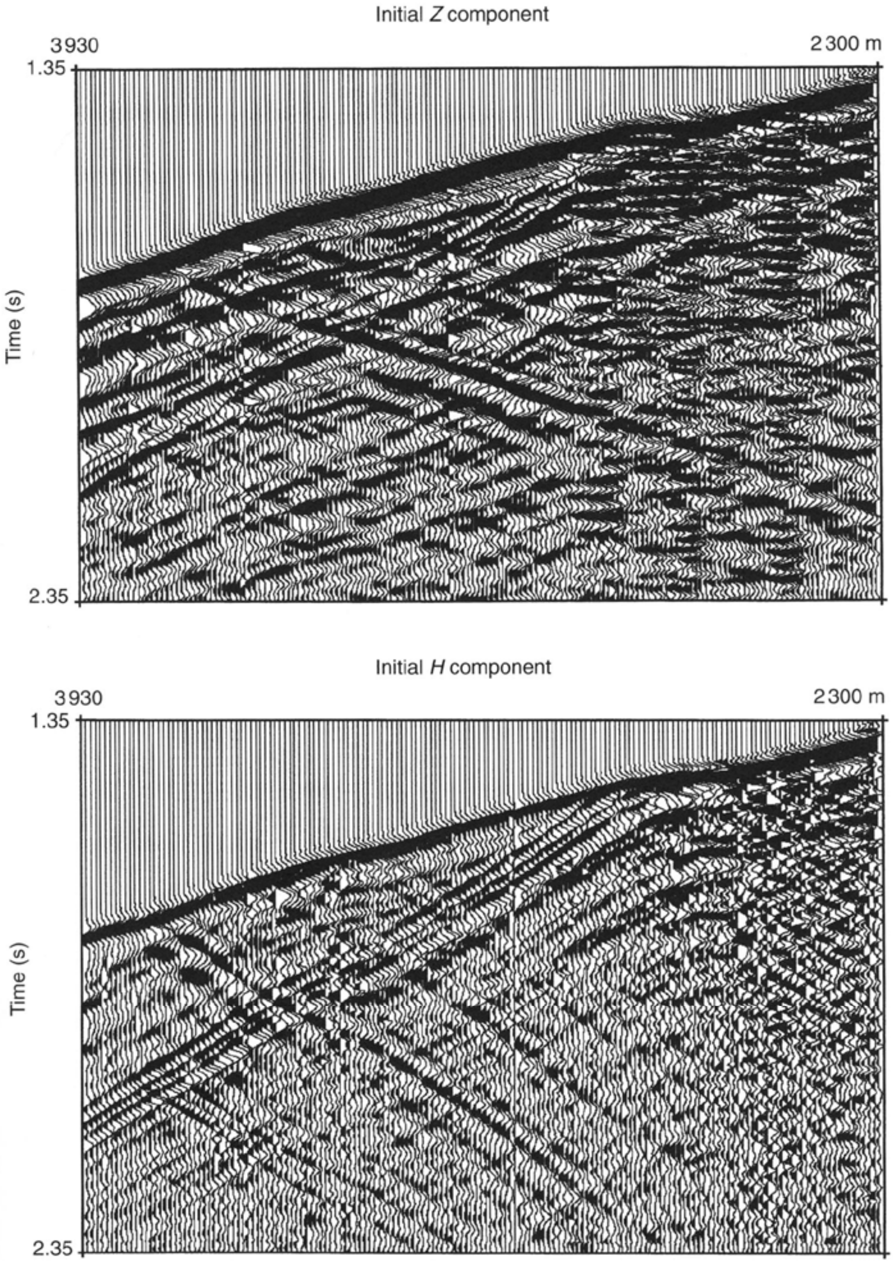


Figure 2.8 *Example of offset VSP recorded with a two-component Z and H well geophone (from J. Mars et al., 1999).*

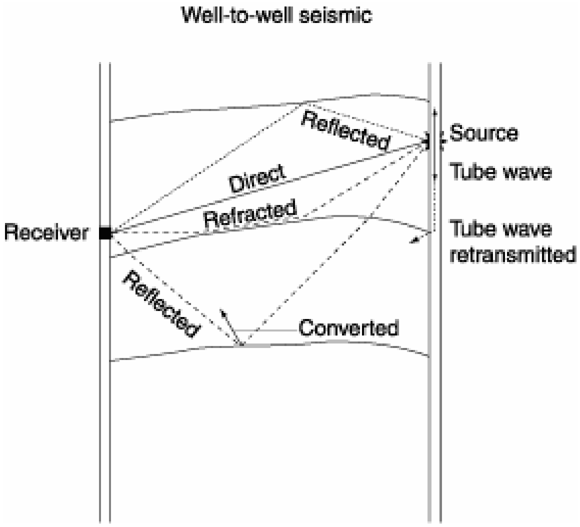


Figure 2.9 *Wave ray paths in well-to-well seismic surveying.*

For well-to-well seismic surveying (Figure 2.9), the observed wave field is complex. In general, the following waves are observed:

- Direct wave.
- Waves reflected and/or refracted on markers located above or below the depth of the receiver, with and without conversion phenomena.
- Conversion waves created by tube waves generated by the source. These conversion phenomena (tube waves-volume waves) occur at layer boundaries associated with strong acoustic impedance contrasts and at the bottom of the well.

When two or more wells are available, a tomographic survey can be performed to finely describe the area between the two wells. Several implementations are possible:

- Transmission tomography.
- Reflection tomography.
- Diffraction tomography.

Figure 2.3 -right is an example of transmission tomography in civil engineering, conducted in vertical wells ahead of a tunnel digger used for laying out a large diameter sewer pipe. It shows a significant alteration of the rocks in the project zone.

Reflection tomography can also be used to image the zone between wells by processing data such as those obtained in an offset VSP (Figure 2.3 left). The source is located in one of the wells, and the receiver in the other. In the example presented, the source is a weight drop generating S-waves. After processing, the resulting S-wave section shows a better vertical resolution than that obtained with a P-wave VSP acquired in the receiving well. In civil engineering, well-to-well seismic surveying is commonly used to determine the S velocities of formations. An example is presented in Chapter 1.

## 2.4 Processing sequence

Conventional VSP processing enables time-depth relationship and velocity logs to be obtained at the well, along with the VSP stacked trace, which is comparable to a very high-resolution seismic trace, without multiples. We assume here that the source and receiver are located on the same line perpendicular to the layers.

The processing sequence includes:

1. Editing (elimination of poor quality recordings)
2. Correlation by sweeps for a vibrator source and if processing was not carried out at acquisition
3. Correction of signature fluctuations (time and amplitude) using the reference geophone
4. Summing of same depth records
5. Component sorting, if a multi-component receiver is used
6. Picking of first arrival times and calculation of the time-depth relationship, and then of velocity logs (interval velocity, average velocity and RMS velocity)
7. Separation (by apparent velocity filter) of volume and guided waves, upgoing and downgoing waves
8. Flattening of upgoing and downgoing volume waves (P or S)
9. Deconvolution of upgoing volume waves by downgoing waves
10. Generation of the VSP stacked trace. Deconvolved and flattened upgoing waves are stacked within a corridor immediately following the first arrival times
11. Optional analysis of the amplitudes of the downgoing volume waves and calculation of attenuation log
12. Optional guided wave amplitude analysis (VSP with hydrophone)

In the different separation methods, the separation of upgoing and downgoing waves is based, explicitly or implicitly, on the fact that both wave types have positive or negative apparent velocities. These wave separation methods can be divided into two categories (Mari and Coppens, 2003; Mari, 2015):

- Methods requiring flattening of the well seismic section at the time of the first arrival, before applying the separation algorithm.
- Methods that do not require flattening.

The methods or filters belonging to the first category include:

- Sum and difference filter
- Median filter
- Wiener filter
- Apparent-velocity filter, if the distance between adjacent recording depths is irregular
- Filtering by singular value decomposition (SVD).

Filters belonging to the second category include:

- Filters based on the spectral matrix (SMF)
- Parametric methods
- Apparent-velocity filter (such as the f-k filter, frequency wave number) if the distance between recording depths is regular.

Separation methods that are not based on a criterion of apparent velocity also exist, namely polarization filters to extract P and S-waves.

It is often necessary to combine several methods to obtain an optimum wave separation. For instance, for an offset VSP, an apparent-velocity filter is used (f-k filter for example) to separate upgoing and downgoing waves, followed by a polarization filter to separate P and S-waves. An example of f-k filter wave separation and polarization filter is shown in Figure 2.10. The initial data are shown in Figure 2.8. On each component (Z, H), we observe upgoing and downgoing waves which can be separated by an apparent velocity filter. In this case, an f-k filter was applied. After separation, each wave type (upgoing or downgoing) comprises P compression waves and S shear waves, which have similar apparent velocities. The P and S-waves are separated by polarization. Figure 2.10 shows the result of the extraction of downgoing and upgoing P and S-waves. The downgoing P appears throughout the entire recording. The downgoing S-wave only appears after a certain depth, corresponding to the marker on which the conversion phenomenon occurs.

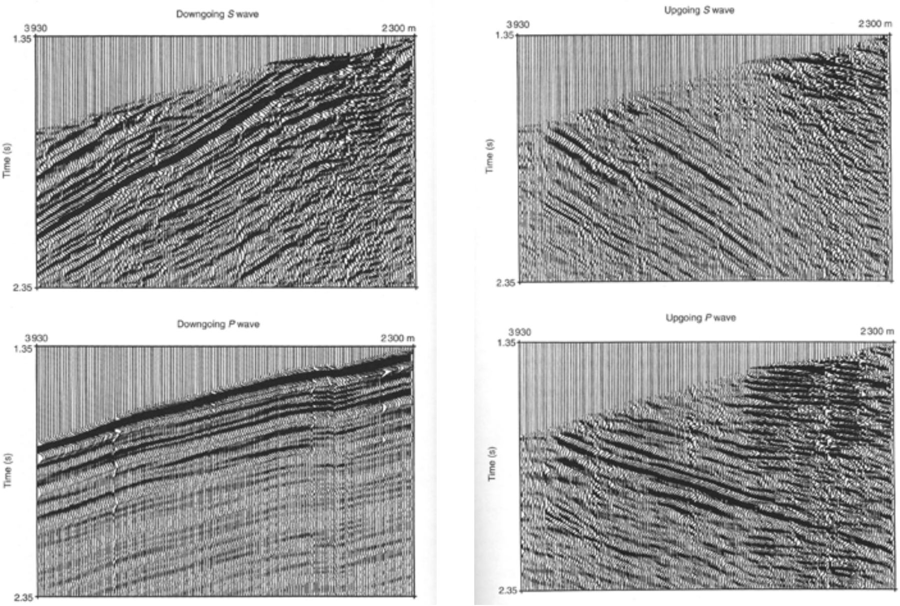
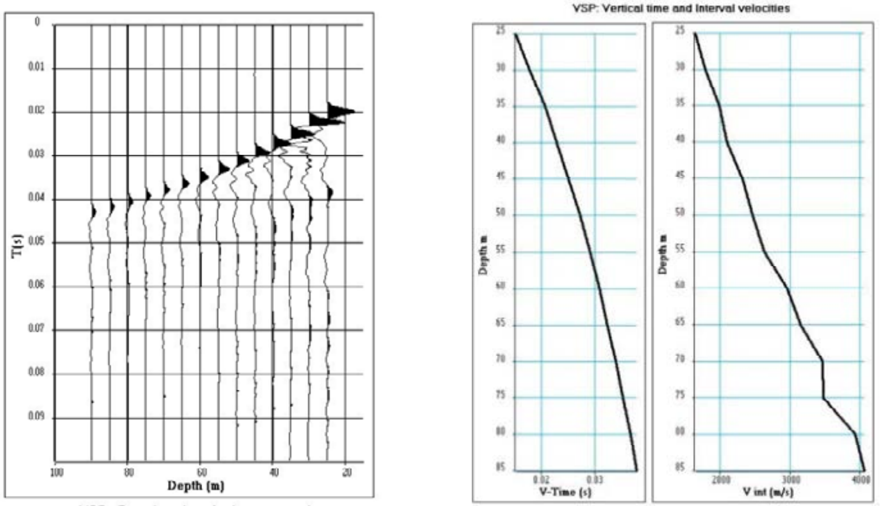


Figure 2.10 *Separation of downgoing and upgoing waves by polarization filter (from Mars et al., 1999).*

Figures 2.11 and 2.12 show the results of the near surface VSP processing, acquired in the 25 to 90 m depth interval. The source is a weight drop (Figure 2.5), the well receiver is an anchored geophone (Figure 2.4a). There is a 5 m distance between 2 measurement points. The listening time is 250 ms. The time sampling interval is 0.25 ms.

The previously described processing sequence was applied. The results of the processing are shown in Figures 2.11 and 2.12. The upgoing and downgoing waves were separated by an f-k filter. A reference geophone, sited near the wellhead, was used to check the repeatability of the source in terms of time (TB fluctuation) and amplitude (energy). This process is essential for attenuation measurements (Figure 2.12c).



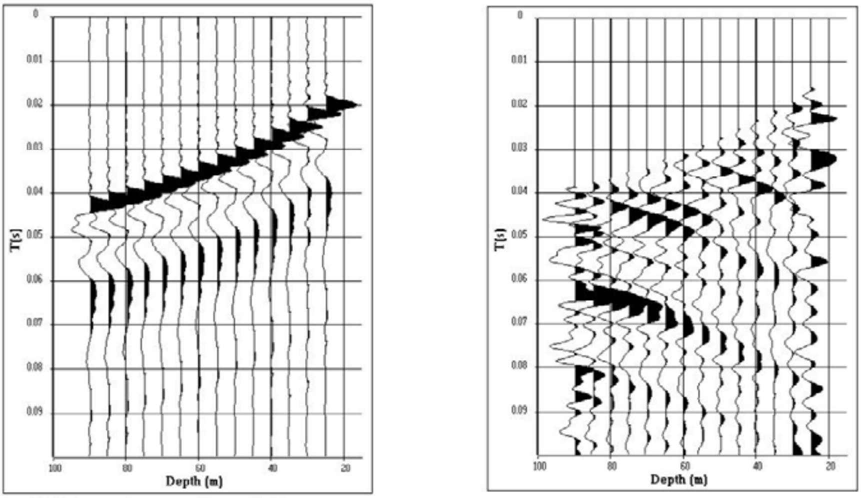
VSP : Raw data ( vertical component)

document IFP School , J.L.M., 2015.

a

document IFP School , J.L.M., 2015.

b



VSP : Down going waves after amplitude recovery

document IFP School , J.L.M., 2015.

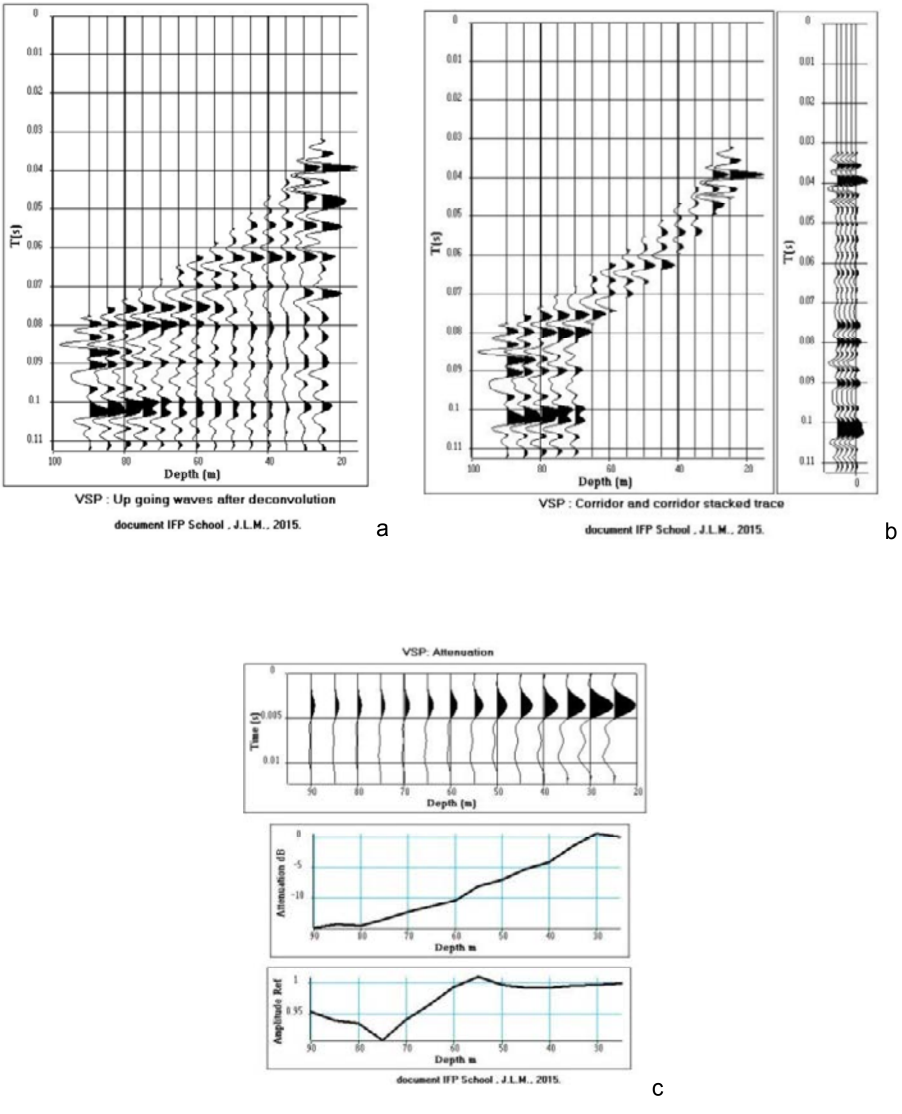
c

VSP : Up going waves after amplitude recovery

document IFP School , J.L.M., 2015.

d

Figure 2.11 *Processing of a near surface VSP. a: raw data, b: vertical time and interval velocities, c: downgoing waves, d: upgoing waves.*



VSP : Up going waves after deconvolution

document IFP School . J.L.M.. 2015.

VSP : Corridor and corridor stacked trace

document IFP School . J.L.M.. 2015.

document IFP School . J.L.M.. 2015.

Figure 2.12 *Processing of a near surface VSP. a: deconvolved upgoing waves, b: stacking corridor and stacked trace, c: attenuation measurement (VSP traces, attenuation log, reference).*

After wave separation, if the source and receiver are not located on the same line perpendicular to the layers, there is a difference in the processing sequence leading to a seismic image that is optimum for a geological interpretation. This is the most general situation that applies to the following cases, offset VSP, VSP in a deviated well, seismic walkaway and well-to-well seismic surveys. The processing sequence includes:

- Deconvolution of upgoing waves. The deconvolution operator is unique.
- It is extracted from traces at the bottom of the well and enables the removal of source signal effects.
- Normal moveout correction and conversion into two-way time of deconvolved upgoing waves. The purpose of this correction is to compensate for the obliquity of the raypaths induced by the source offset. The aim is to take the acquisition geometry into account. Knowledge of the velocity model is necessary to perform this correction.
- Migration: the method most commonly used with VSP is the one proposed by Wyatt and Wyatt (1982). The VSP seismic section obtained after migration is directly comparable to a surface reflection seismic section. The migrated VSP section has a lateral range of investigation of a few tens to a few hundreds of meters.

The example shown here concerns data recorded in a highly deviated well on the Wytch Farm Field on behalf of BP-Amoco and partners.

Well data were acquired in the F18 deviated well (which reached a maximum deviation of 88.5°) with a vibrator source located at a distance of 1,865 m (Jerry's Point (JP)) with respect to the wellhead. Recordings were carried out with a CSI-type 3-component well geophone (Schlumberger's Combinable Seismic Imager Tool). The well geophone was equipped with sensors with a natural frequency of 10 Hz. Acquisition filters were a 2 Hz low-cut filter with a 6 dB/oct slope, and a 330 Hz high-cut filter with a 30 dB/oct slope. The source signal was emitted within the 10 to 80 Hz bandpass range. The duration of the frequency sweep was 16 seconds.

The velocity model used to process seismic data was created using the information provided by surface seismic and velocity curves from all wells in the vicinity of the F18 well. The velocity model was refined by inversion of first arrival time picks, minimizing the difference between measured times and the times calculated by the inversion algorithm. The difference between the calculated and measured times did not exceed 3 ms. Figure 2.13 shows the velocity model, the well trajectory, the different positions of the well geophone and the location of source points. For each source point, ray tracing shows the path followed by the downgoing wave.

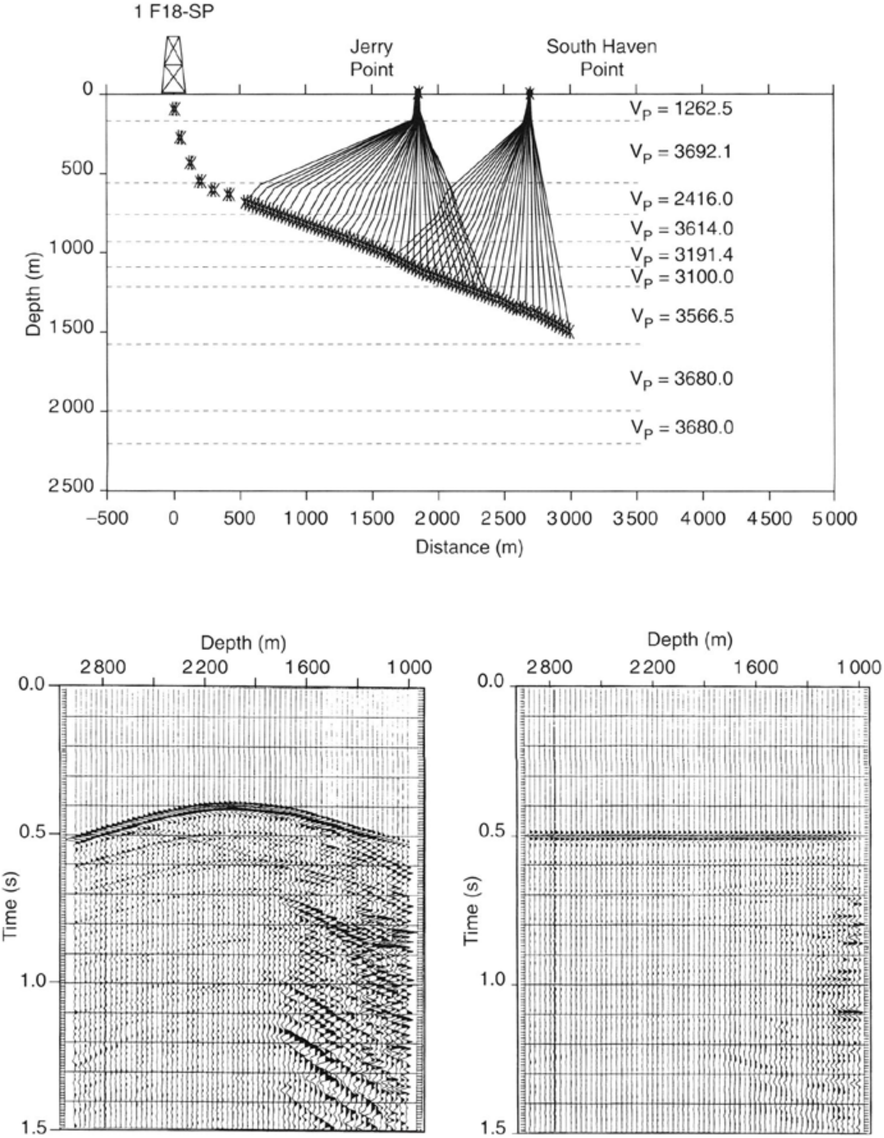


Figure 2.13 *VSP in deviated well (BP exploration document). Top: Velocity model and well trajectory. Bottom: VSP data after amplitude recovery and downgoing waves.*

Figures 2.13 to 2.15 illustrate the processing sequence applied to well data obtained with the source located at Jerry Point (JP). The processing phases are as follows:

- Frequency filtering and amplitude recovery. Seismic data were filtered in the 5 to 80 Hz bandpass and compensated for the spherical divergence effect by application of a gain law. Each VSP trace was then normalized to the direct arrival to compensate for transmission losses. The result of this pre-processing is shown in Figure 2.13 (bottom left). The horizontal axis of the VSP section represents the cable length deployed along the well.
- Picking of first arrival times and wave separation. The VSP section was flattened on the first arrival time picks. A 7-term median filter was applied to flattened data to extract the downgoing waves (Figure 2.13 bottom right). The downgoing wave section was subtracted from the initial data. The residual section was then corrected by the first arrival times to restore each VSP trace to its initial time. The residual VSP section (Figure 2.14 top left) mainly shows the upgoing waves.
- Deconvolution. A Wiener-Levinson deconvolution (Mari, 2015) was applied to the downgoing waves (Figure 2.14 top right) and to the upgoing waves (Figure 2.14 bottom left). The operator, calculated on the downgoing field for the purpose of transforming the downgoing wavelet into a zero-phase signal, was applied to the upgoing and downgoing fields. A different operator was calculated for each VSP depth.
- Generation of the seismic image. The seismic image is obtained from the section representing the deconvolved upgoing waves. The operation involves 4 steps:
    1. Calculation of the velocity model
    2. NMO corrections and conversion of upgoing waves in two-way times (Figure 2.14 bottom right)
    3. Calculation of equal-abscissa lines for mirror points. Figure 2.15 (left) shows the distribution of equal-abscissa lines (iso-X lines) on the section displayed in Figure 2.14 (bottom-right) after application of a gain law. The distance chosen between two iso-X lines was 25 m
    4. Migration using the method presented by Wyatt (1981). The migrated VSP section is shown in Figure 2.15 (right). The horizontal axis represents the horizontal distance between the well (0 m) and the different mirror points. The distance between two mirror points is 25 m. The lateral range of investigation of the VSP section is of the order of 1,000 m. The section is displayed in normal polarity according to the SEG convention. Under normal polarity, an upgoing compression wave reflected by a marker associated to an increase in acoustic impedance is represented by a negative amplitude value (trough)

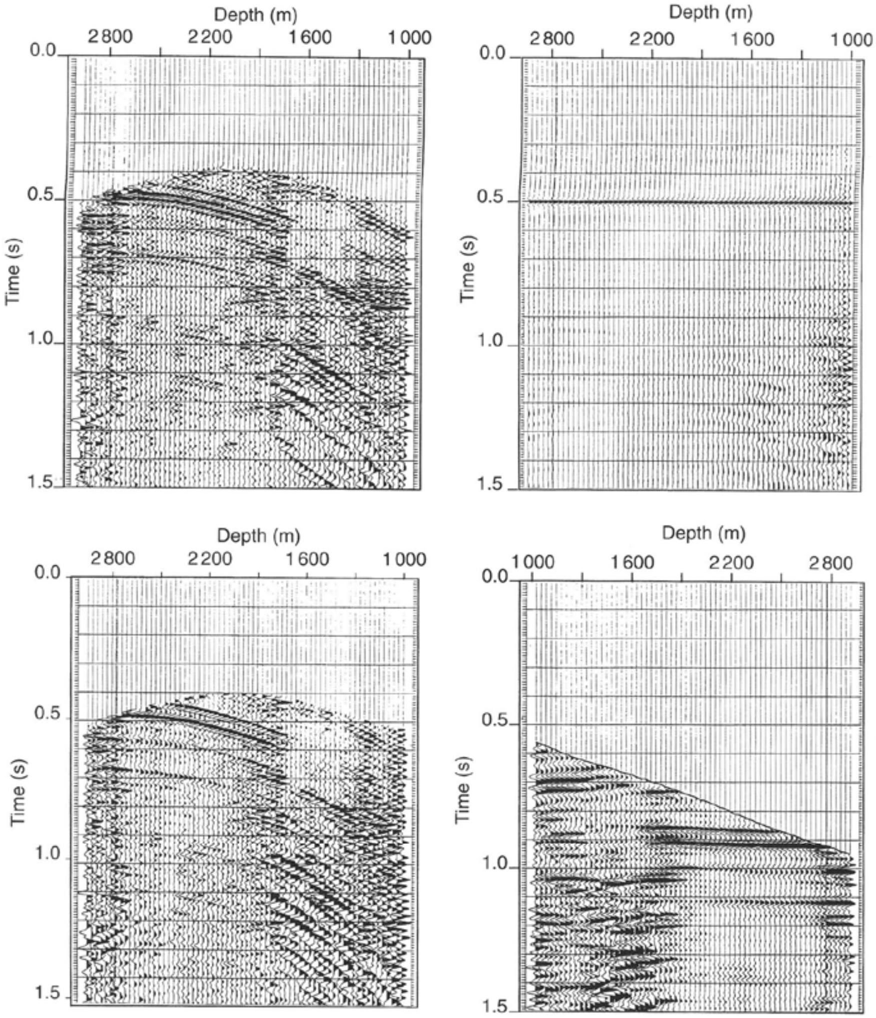


**Figure 2.14** *VSP in deviated well (BP exploration document). Top: Residual VSP section and deconvolved downgoing waves. Bottom: Upgoing waves after deconvolution and after NMO correction.*

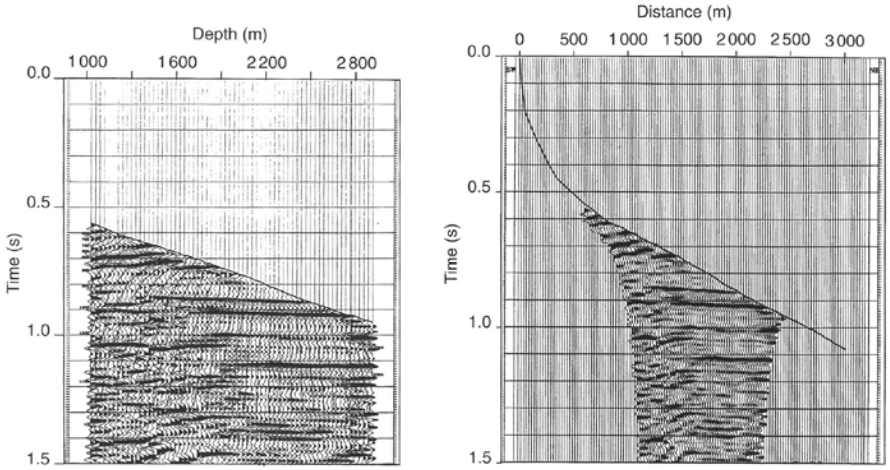


**Figure 2.15** *VSP in a deviated well (BP exploration document). Left: Upgoing waves after Wiener deconvolution and NMO corrections. Lines of equal abscissa X (iso-X) displayed every 50 m. Right: Migrated section.*

## 2.5 Application with a geotechnical dataset

The following example comes from EDF's downhole database. This downhole is from the study presented in Chapter 1, paragraph 4, limited to P data acquired with hydrophones (see Figure 2.16).

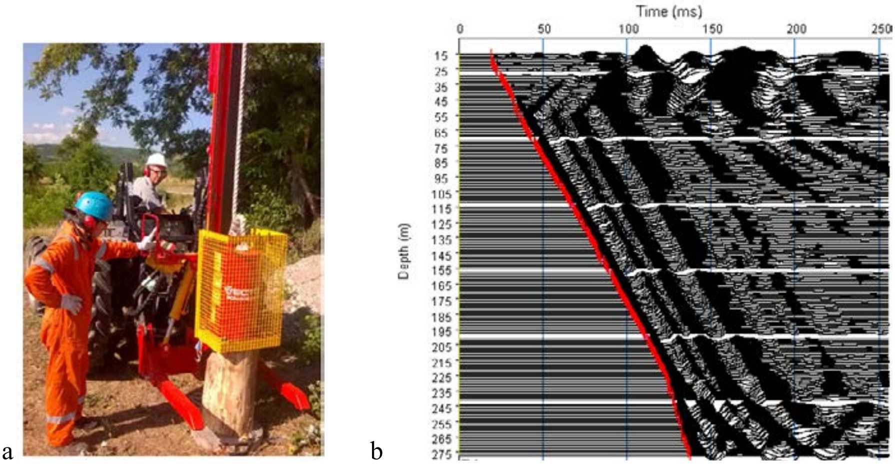


**Figure 2.16** *FUGRO seismic source (a) and downhole recording (b) EDF document.*

The geology of the well can be summarized as follows:

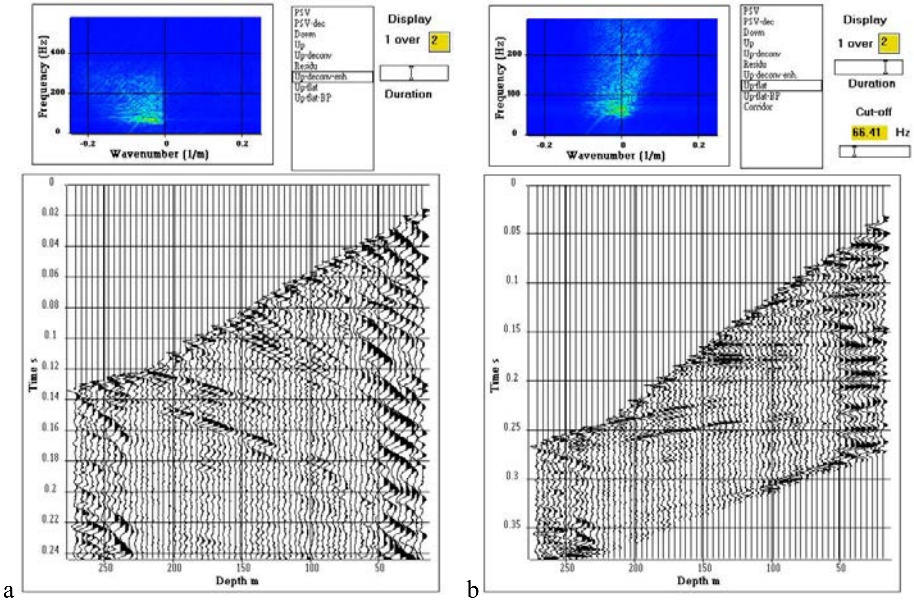
- 0 to 3 m: outer sand layer,
- 3 to 6 m: under sand layer,
- 6 to 21.5 m: sandy-gravelly alluvial deposits,
- 21.5 to 225 m: succession of layers of fine sand, clay and silt; sand layers dominate down to 41 m,
- 225 to 280 m: shale, weathered to varying degrees.

IFP Energies nouvelles applied the following processing sequence:

- normalization of traces,
- spectral equalization deconvolution to attenuate the effect of casing-related waves and to increase the resolution,
- picking of first arrivals and velocity calculation,
- separation of upgoing and downgoing waves by wave number filtering,
- deconvolution of upgoing field,
- flattening of upgoing field by the application of static corrections,
- summation of traces within a corridor.

The deconvolved upgoing field (2.17a) is offset in time by the application of a static correction defined at each depth by the vertical time to put the events associated with subhorizontal reflectors in double time and thus enabling a direct comparison with a surface seismic recording near to the well (2.17b). The diffraction hyperbolas are neither flat nor focused in this phase of processing, as shown by the oblique diffractive event visible before 250 ms in the Figure 2.17b.

The upgoing waves that have been deconvolved by the downgoing field and flattened can also contain upgoing multiples. To eliminate the effects of the upgoing multiples, a narrow stacking corridor was chosen so as to retain only the reflected signal received immediately after the first arrival. The upgoing waves in the stacking corridor are added to obtain a zero-phase multiple-free stacked trace comparable to the migrated surface seismic trace closest to the well. Figure 2.18 also shows that the diffracting event before 250 ms is eliminated by simple summation on the VSP stacked trace.

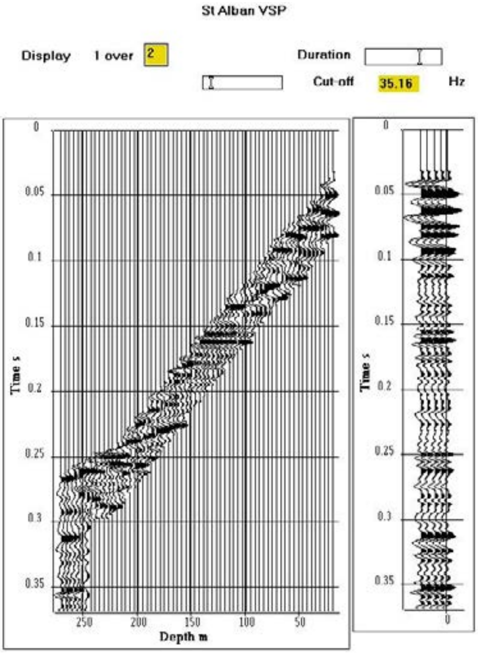


Display 1 over 2

Display 1 over 2

Cut-off 66.41 Hz

Figure 2.17 *a) deconvolved upgoing field (improved signal to noise ratio), b) flattened deconvolved upgoing field.*



St Alban VSP

Display 1 over 2

Cut-off 35.16 Hz

Figure 2.18 *Stacking corridor and VSP stacked trace (35 to 190 Hz).*

The results obtained therefore show that if the data are correctly sampled, a conventional VSP processing sequence can be adapted to downhole data. The VSP stacked trace can thus be used to tie a seismic reflection profile as shown in Figure 2.19.

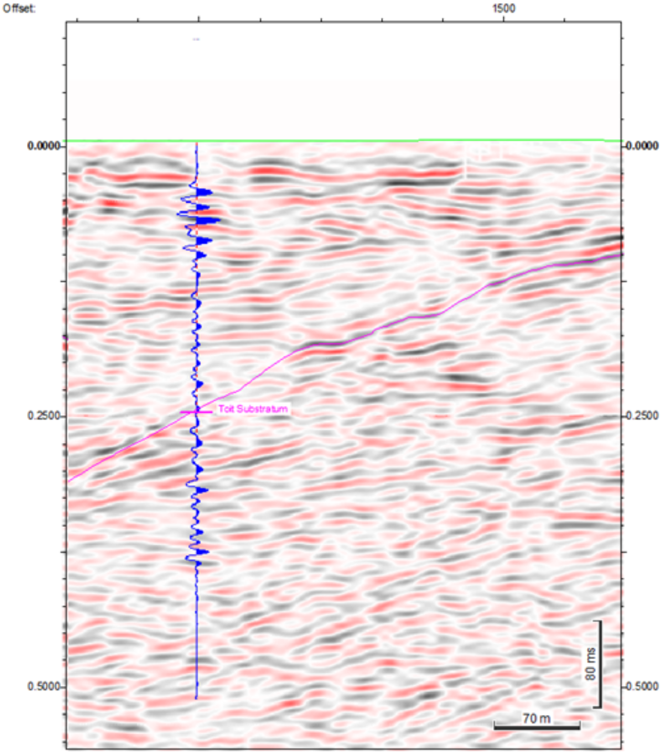


**Figure 2.19** *Tying of a VHR seismic section on the downhole stacked trace (EDF document).*

## 2.6 Conclusion

The main applications of well seismic surveying are:

- Establishing the time-depth relationship at the well position
- Establishing a velocity model (P and/or S)
- Tying seismic refraction profiles
- Validating static corrections

- Providing a detailed image in the area around the well (taking into account the offset of the source)
- In-depth tying of seismic reflection profiles
- Identifying primary and multiple reflections
- Providing structural information, estimating reflector dip (3 component recording)
- Locating fracture zones (hydrophone measurements) and fault plans (oriented 3C receiver)
- Predicting the presence of reflectors or anomalous zones (e.g. under compaction) ahead of the drill bit, i.e. below the well for a vertical well, and ahead of the drilling front for a horizontal well

The following elements must also be considered:

- The main limitation is the lateral investigation around the well. In classic VSP, with a source offset by several meters, it is limited between the vertical resolution (quarter of wavelength) and around ten meters
- A poor coupling of the probe to the formation leads to the presence of noise, especially for the horizontal components of the well receiver.
- The anchoring force of the well receiver may be insufficient in the case of large diameter wells, resulting in poor coupling.
- Well conditions, such as with poorly cemented cased wells, can make measurements difficult. A good coupling of the well sensor to the casing does not guarantee a good coupling of the receiver to the formation. It is then necessary to make a cementation log before carrying out a VSP.
- The presence of guided waves (Stoneley waves) can be detrimental to the extraction and analysis of volume waves (mainly for hydrophone acquisition).
- Acquisition is sensitive to industrial, human and natural vibrations. It is important to avoid cable transmissions by slackening the cable when measuring.
- The acquisition duration can be estimated at 5 to 10 mn/depth, for a classic VSP.

The offset VSP and the seismic walkaway enable an extension of the lateral investigation variable with depth and provide a detailed seismic survey of the vicinity of the studied objective.

Although the well seismic lateral investigation is in any case limited, having receivers close to the objectives provides a good vertical resolution, due mainly to the fact that the surface weathering zone is crossed just once.

## References

Hardage B.A., 1985, *Vertical seismic profiling, Part A: principles*. Geophysical Press, London.

Hardage B.A., 1985, *Vertical seismic profiling, Part B: advanced concepts.* Geophysical Press, London.

Hardage B.A., 1992, *Cross well Seismology and Reverse VSP*. Geophysical Press, London.

Huang C.F., Hunter J.A., 1981, The correlation of tube wave events with open fractures in fluid filled boreholes: current research, Part A, *Geological Survey of Canada*, paper 81-1A, 361-376.

Mari J.L., 1989, Q-log determination on downgoing wavelets and tube wave analysis in vertical seismic profiles. *Geophysical Prospecting*, 37, 257-277.

Mari J.L., Arens G., Chapellier D., Gaudiani P., 1999, *Geophysics of reservoir and civil engineering*, Éditions Technip, Paris, ISBN: 2-7108-0757-2.

Mari J.L., Coppens F., 2003, *Well seismic surveying*. Éditions Technip, Paris, ISBN: 2-7108-0776-9.

Mari J.L., 2015, Signal processing for geologists & geophysicists, e-book, DOI:10.2516/ifpen/2011002, http://books.ifpenergiesnouvelles.fr/ebooks/signal-processing/

Mars J., Glangeaud F., Boelle J.L., Vanpe J.M., 1999, Wave separation by an oblique polarization filter, PSIPP'99. First international symposium on Physics in Signal and Image Processing, 18-19 January 1999, Paris, France, 94-108.

Wyatt K.D., Wyatt S.B., 1982, Determination of subsurface structural information using the vertical seismic profile. *Geophysics*, 47, 7, 1123-1128.