Synthesis

J.-L. Mari, M. Mendes, H. Chauris

The 7 chapters in this book provide a practical overview of seismic imaging:

Chapter 1 is a brief review of the current state of knowledge in seismic propagation. It introduces the different seismic methods for prospection. Several examples are used to show the different waves, which can be observed on field records and are predicted by the wave equation. The chapter underlines the fact that the acquisition geometry (2D or 3D) and the type of seismic survey (surface or well) must be taken into consideration in the wave identification.

Chapter 2 is dedicated to refraction surveying. Seismic refraction can be used for investigations at all depths, but for various technical reasons it is mostly used in the study of the first 300 metres of the subsurface (spread length, importance of the source energy, …). Refracted P-waves are currently used to obtain a velocity model of the near surface by combining conventional methods such as the T plus – T minus or GRM method and tomography. The refraction method is currently used in hydrogeology and in civil engineering. We have presented 2 applications of the refraction method: the computation of static corrections, and the characterization of a near-surface karstic reservoir.

DOI: 10.1051/978-2-7598-2351-2.c010

For conventional studies, the refraction method requires only the measurement of arrival times of first arrival waves (direct and refracted waves) to provide a geological model. Amplitudes are not commonly used in seismic refraction studies. In the case of an irregular interface, the analysis of the distortion of the head wave arrival allows the detection of wave interferences, which can be associated with the presence of fractures (second field example).

In **chapter 3**, the task of imaging near-surface structures has been addressed with a few seismic tomography approaches. Several seismic field datasets are used to illustrate the ability of tomographic tools.

The first field example concerns a transmission tomographic technique used for inverting first-arrival times, picked from a 3D surface seismic dataset, which was part of a geophysical survey conducted in a karstified dolostone region. Due to the limited azimuthal coverage of the surface data, the tomographic inversion produced a 3D model for the karst aquifer, with significance only in the upper epikarst region (up to 7 m deep). To overcome this image depth limitation, data collected with down-hole receivers were used simultaneously with those from surface geophones, which extended the image depth to the underneath low-permeability volume (up to 28 m deep). This 3D approach revealed a set of elongated furrows at the base of the epikarst and identified heterogeneities deep inside the low-permeability volume that may represent high-permeability preferred pathways for water inside the karst.

In the second field example, the seismic data were collected by triaxial geophones in a cross-well experiment using a reflection tomography procedure, which enabled the imaging of a limestone reservoir at a depth of about 1,850 m. The raw field data were processed like conventional offset VSP data and the information present in the travel time of reflected S-waves was exploited for imaging between the boreholes. The imaging was achieved by time and depth transformations using a VSP-CDP stack, guided by a S-S ray tracing with a velocity model based on previous P and S VSP analysis. Although the reflection tomography did not provide an image with high frequency waveform, it successfully demonstrated the possibility of imaging between two wells from seismic data collected with conventional borehole multi-component sensors and seismic waves generated by a low-energy source.

Finally, through the application of a diffraction tomography approach, based on the Born approximation, we were able to produce quantitative elastic depth images from multi-component offset VSP datasets. One dataset was collected in the North Sea, and another from acoustic and multi-component borehole data collected at two different boreholes in the Paris basin.

The target zone of the North Sea survey, which covered the reservoir area, is a rectangle extending from 50 m to 550 m east of the borehole, with depths from 3,400 m to 4,400 m. Geologists were able to interpret the estimations of three elastic parameters – P and S-wave velocities and density – that were produced by the diffraction tomography. Then, the top of the Brent reservoir could be delineated continuously away from the borehole, while it was also possible to interpret two faults. This chapter also includes a discussion on the assessment of the elastic depth image quality that should be given directly by the residuals between field data and seismograms computed with the elastic images.

The last example presented in this chapter is based on data from a one-shot seismic survey in the Paris basin. This study includes processed acoustic and multi-component data collected at two different wells with inter-well distances of about 100 m. Only upgoing S-S and S-P reflected events were used for the tomography. The target zone included three sand reservoir levels between depths of 575 and 600 m. Due to insufficient source and receiver coverage of the target zone (because it was only a one-shot survey), the diffraction tomography produced unreliable images with strong artifacts on the upper section, i.e. above 560 m. However, tomography proved capable of producing high-resolution (≈ 3-5 m) images for the reservoir region. The comparison of both density images with a pseudo-density log, produced by a density log convolved with a characteristic signal with the same bandwidth as the density image, is quite satisfactory within the reservoir region.

In conclusion, based on the good results obtained from the field studies, it can be said that seismic tomography has the potential to provide superior images that are capable of addressing the problem of near-surface structure characterization.

Chapter 4 is dedicated to near-surface reflection surveying. After a short review of the design of conventional 2D and 3D surveys, we briefly summarize the main steps of a processing sequence. With two field datasets, we showed that it is possible to obtain very high-resolution 3D blocks for near-surface applications with very light seismic spreads (48 channel recorders, a single geophone per trace, and a light seismic source). Near-surface studies require specific test phases to define the optimum parameters (minimum offset, geophone interval) for the acquisition. The processing sequence must be carefully adjusted to the field data, especially for the wave separation. In the example of the imaging of the near-surface karstic reservoir (Hydrogeological Experimental Site of Poitiers), we showed that the velocity distribution obtained by refraction tomography in the first 30 m can be merged with the velocities extracted from the amplitude of the reflected events to obtain a continuous velocity model from the surface to a depth of 120 m.

Chapter 5 discusses the huge potential of Full Waveform Inversion (FWI) in terms of quantitative seismic image interpretation. In practice, the applicability of the method depends on the quality of the data, as well as on the most appropriate pre-processing (for example to preserve the low frequency data) and on the correct physical understanding of the wave propagation phenomena. In future elastic FWI will replace the acoustic approach, and the technique will be able to extract more than a single parameter (e.g. velocity and attenuation). Also, it may be possible to incorporate higher frequencies. On the exploration scale, FWI is still in its infancy. We hope that this chapter will positively encourage the reader to evaluate for themselves the use of FWI on near-subsurface data sets.

Chapter 6 discusses handling different types of waves present in the same set of experimental data. We have underlined some of the advantages of hybrid seismic imaging strategies to provide efficient, accurate and reliable subsurface models, in terms of geometry and mechanical properties. In the first field example, the hybrid seismic imaging tool showed that seismic data derived from traditional refraction acquisition is valuable for obtaining information about the reflectivity for targets located in the near and/or very near surface. After first break pickings, a P-wave tomography inversion was performed to obtain a depth velocity model. The processing of reflection events, present in the seismic refraction survey, was carried out by a standard procedure. However, particular attention was focused on isolating the reflection waves. Finally, after a careful adjustment of the results obtained from the processing of refraction and reflection waves, they were gathered to produce an extended time reflectivity section starting from the surface. In the second example, a refraction tomography algorithm has been applied to the first-arrival times picked manually on the shot gathers collected in a hydrothermal area. A P-wave velocity model was obtained that presented values in the range 100 – 2,000 m/s and a low velocity layer at the surface with thickness around 5 m. The processing of surface waves, extracted from the seismic survey, was performed in the f-k domain with SWIP, an open-source MATLAB-based package. The inversion of the dispersion curves produced a set of 1D models of S-wave velocity with an estimated depth of investigation of around 10 m. The final result was a pseudo 2D model obtained by merging all of the best fitting 1D models. The final S-wave velocity model showed strong lateral variations that were not visible on the P-wave velocity model, probably due to strong saturation variations. This information was used to estimate the Poisson's ratio. The distribution of this parameter, more particularly its contrasts, clearly highlights gas pathways in the subsurface that are consistent with the degassing observed at the surface. Thus, these positive results open up new perspectives for several applications of more hybrid seismic methods.

Finally, **chapter 7** presents a field study at a site that has been extensively studied by the French national radioactive waste management agency (Andra). We showed how the integration of seismic data (3D survey and VSP), logging data (acoustic logging), and core measurements, combined with a succession of specific and advanced processing techniques, enabled the development of a 3D high-resolution geological model in depth. We demonstrated the benefit of geostatistical processing, both to quantify the quality of the seismic amplitude (SQI) and to perform depth conversion (Bayesian Kriging). The Q factor of geological formations can be obtained from VSP data. We used the fact that attenuation introduces dissipative dispersion, which can be measured from the frequency-dependent phase velocity of the VSP down-going wave. The methodology has been extended from well data to surface seismic data. For this purpose, a high-resolution velocity model is required. This was obtained from elastic inversion of the seismic data and by conversion of acoustic impedance *Ip* in velocity *Vp*. The procedure can be used to build a geomodel in depth defined by mechanical and hydro-geological parameters: velocities (*Vp, Vs*), density, Q factor, porosity, specific surface, and index of permeability. The seismic procedure was extended to compute a seismic pseudo gamma ray (GR-Seis). A high porous layer was detected at the top of the Dogger and lateral variation of the shale content can be seen in the Callovo-Oxfordian.