Summary of the PhD thesis

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ESTIMATION OF FREQUENCY-DEPENDENT ATTENUATION OF SEISMIC WAVES USING WAVEFORM INVERSION OF BOREHOLE SEISMIC DATA

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The PhD thesis has been prepared at the (1) Department of Seismometry and Geoacoustics of the Geological Faculty of Lomonosov Moscow State University and the (2) Department of Exploration Geophysics of Curtin University. The thesis is the outcome of the joint PhD program.

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The PhD thesis (in Russian) can be found in the dissertation department of the scientific library of Lomonosov Moscow State University (str. Lomonosovsky Avenue, bld. 27) and on the website of the IAS "ISTINA": https://istina.msu.ru/dissertations/244255612/

General description

Relevance of the topic

Knowledge of the factors that control frequency-dependent attenuation of seismic waves in the subsurface can be useful for both seismic imaging and amplitude-based characterization of geological objects. Neglecting the effects of frequency-dependent attenuation during processing and interpretation of seismic data leads to errors in predicting of reservoir properties, which may entail economic risks for hydrocarbon field exploitation.

Conventional approaches to estimating seismic attenuation such as amplitude decay method, spectral-ratio method and similar techniques assume that a wave propagates in a homogeneous medium described by a constant quality factor Q (an inversely proportional measure of attenuation). The assumption of the homogeneous earth makes the conventional methods sensitive to the interference of seismic waves, which leads to large uncertainties and poor vertical resolution of Q-estimates. Besides, the conventional methods estimate effective attenuation, Q_{eff}^{-1}, which comprises the cumulative effect of scattering by small-scale heterogeneities, Q_{scat}^{-1}, and intrinsic absorption in rocks, Q_{int}^{-1}. Separation of these factors may be of interest for quantitative description of the subsurface. Several case studies reveal that the contribution of the frequency-dependent scattering to the effective attenuation may be significant and hence should be taken into account at the processing stage.

In general, the development of methods for assessing and analyzing the frequency-dependent seismic attenuation would enhance the quality of the subsurface characterization based on the exploration seismic data.

Degree of scientific development of the topic

In Russia, a significant contribution to the study of frequency-dependent attenuation of seismic waves in inelastic and scattering media was made by Sh. A. Azimi, A.V. Kalinin, O.K. Kondrat'ev, M.B. Rapoport, S.A. Shapiro, B.Ya. Gurevich, I.V. Morozov and many others. D.B. Finikov, M.S. Denisov, V.I. Ryzhkov were involved in developing methods of estimation and compensation of frequency-dependent attenuation. Abroad, the topic was actively developed by Ricker N., Futterman W.I., Strick E., Liu H-P., O'Doherty R.F., Anstey N.A., Kjartansson E., Banik N.C., Toksoz M.N., Johnston D.H., Ganley D.C., Harris P.E., Tonn R., Amundsen L., Clark R.A., Margrave G.F., Müller T.M. This list is not exhaustive.

The **purpose** of the thesis is to develop a methodology for the stable assessment of the parameters of frequency-dependent attenuation of seismic waves in the exploration seismic frequency band, 5-150 Hz.

To achieve the goal, the following **tasks** were solved.

1. Review, comparative analysis, and classification of existing methods for estimation of frequency-dependent seismic attenuation.
2. Study of elastic scattering by vertical microheterogeneities in real geological environments.
3. Development and approbation of a technique for inverting the seismic wavefield recorded by vertical seismic profiling (VSP) in a borehole to estimate the parameters of frequency-dependent attenuation in the near-wellbore space.
4. Applicability study of the developed inversion technique on the synthetic borehole seismic data.
5. Application of the developed inversion technique on the field borehole seismic data to build the models of elastic scattering and inelastic absorption in real geological environments.

The **objects** of this work are inelastic and thin-layered scattering geological media and methods of their study.

Scientific novelty

1. For the first time, estimates of elastic scattering in the interval of a carbonate section on the shelf of Western Australia have been obtained, and its impact on seismic data quality has been estimated.
2. An original technique of a constrained 1D waveform inversion of VSP data has been proposed, substantiated, and tested on the model and field seismic data. The technique allows one to quantitively assess the inelastic absorption of seismic waves in the near-wellbore space and restore the signature of a seismic signal.
3. New data have been obtained on the absorption and scattering of seismic waves in several hydrocarbon basins in Australia and at the Otway research facility for geosequestration of carbon dioxide CO_2 into the subsurface. With the inverted models of seismic absorption, a productive gas-saturated reservoir has been identified in one of the fields of North West Shelf (Australia). At the Otway research site, it has been shown that the injection of a mixture of carbon dioxide and methane, CO_2/CH_4, into a thin layer with a thickness of about 0.3 of the wavelength does not affect the spectral characteristics of the seismic signal (frequency band up to 150 Hz).

Defended statements

1. In horizontally layered media, where the spread of elastic properties is characterized by a standard deviation of more than 10 %, and the thicknesses of the high-contrast layers are of the order of 0.02-0.2 of the wavelength, elastic scattering leads to the apparent frequency-dependent attenuation of signals in a seismic frequency band (5-150 Hz), which cannot be separated from inelastic absorption by standard attenuation estimation methods, such as spectral ratio or central frequency shift methods.

2. The proposed waveform inversion of VSP data allows for stable estimation of frequency-dependent attenuation of seismic waves at small measurement bases in the near-wellbore formation if a horizontally layered model can approximate the geological medium.

3. Provided the sonic and density logging data are available, the proposed methodology of the waveform inversion of VSP data allows for the separation of elastic scattering and inelastic absorption in horizontally layered media.

Practical significance

The results and conclusions of this work allow a stable assessment of the parameters of frequency-dependent attenuation of seismic waves in the near-wellbore space in various geological environments. Quantitative estimation of seismic attenuation parameters is of practical importance for the subsurface characterization based on the exploration seismic data.

Reliability

The reliability of the results presented in the PhD thesis is proved on the synthetic (model) and field VSP data obtained in different geological conditions. The results presented in the first chapter are consistent with the theory. The author reported the main results and deliverables of the thesis at Russian and international conferences:

- In 2018 and 2019, at the international geological and geophysical conference and exhibition "Modern technologies for the study and development of the subsurface of Eurasia - GeoEurasia", Moscow, Russia.
- In 2018 at the international conference "Australasian Exploration Geoscience Conference - Exploration · Innovation · Integration", Sydney, Australia.
- In 2017 and 2018, at the annual international conference and exhibition "European Association of Geoscientists & Engineers (EAGE) Conference and Exhibition", Paris, France, June 12-15, 2017; Copenhagen, Denmark, June 11-14, 2018.
- In 2016 and 2018 at the annual international conference "Society of Exploration Geophysicists (SEG) Annual Meeting", Anaheim, USA, October 14-19, 2018; Dallas, USA, October 16-21.

- In 2017, at the international conference "International Conference on Engineering Geophysics (ICEG)", Al-Ain, O.A.E.

Approbation

The methods and results presented in the PhD thesis were tested in several studies, including the study of frequency-dependent attenuation of seismic waves in subbottom marine sediments on the Russian Arctic shelf. The results obtained in the thesis formed the basis for thirteen publications in the peer-reviewed scientific journals and proceedings of Russian and international conferences.

Data and research methods

In the research study, the following field materials were used:

• well logging and vertical seismic profiling (VSP) data obtained in various geological offshore areas in Western Australia;

• onshore well logging and VSP data from the Cooper Basin (Queensland, Australia);

• onshore well logging and VSP data from CO2CRC's Otway research site for CO_2 geosequestration and monitoring (Victoria, Australia).

The synthetic and field seismic datasets were processed in the specialized geophysical software RadexPro and the MATLAB programming environment using open libraries for seismic data processing CREWES. For joint analysis of 4D seismic data, 4D VSP data and well logging data acquired at the Otway research site, the interpretation software package Petrel was utilized. The modelling of seismic wavefield for horizontally layered inelastic media was carried out in the OASES software developed by the Massachusetts Institute of Technology (MIT) and in the MATLAB environment using the algorithms implemented by the author. The author developed the algorithm for solving the forward and inverse problems and implemented it in the MATLAB environment.

Personal contribution

The author participated in the field acquisition of zero-offset and offset borehole seismic data at the Otway research site in Victoria (Australia) and conducted the subsequent processing of the acquired data. Also, the author independently implemented and tested various approaches to solving the inverse problem of the VSP data. The author has developed a methodology of the 1D waveform inversion of VSP data to estimate the parameters of frequency-dependent seismic attenuation. The programming of the implementation of the proposed methodology and modelling, data processing and analysis of the obtained results were carried out by the author.

Publications

The results of the thesis have been published in thirteen research papers. Of these, three publications are in peer-reviewed scientific journals included in the international citation databases Web of Science (WoS), Scopus, RSCI (RSCI), and included in a list of research journals recommended for publication LMSU dissertation council. Ten publications are in the proceedings of Russian and international conferences indexed in Scopus, WoS, RSCI databases.

Scope and structure of the thesis

The thesis contains an introduction, four chapters, a conclusion, a list of abbreviations and a list of references, consists of 139 pages of text, 44 illustrations and four tables.

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Thanks to my dear spouse, family, and friends for their support and cheerful company.

Main body of the thesis

In the **Introduction**, the relevance, the main goal, and the dissertation research objectives are formulated.

Chapter 1. Frequency-dependent attenuation of seismic waves

Section 1.1 presents basic concepts used in seismic exploration to describe the phenomenon of frequency-dependent attenuation of seismic waves and its associated wave velocity dispersion, $c(\omega)$. Frequency-dependent attenuation coefficient, $\alpha(\omega)$, can be expressed through a seismic quality factor, $Q(\omega)$, that characterizes damping of wave amplitude at a given wavelength:

$$\alpha(\omega) = \frac{\omega}{2c(\omega)Q(\omega)} \quad (1)$$

Also, the most common models of the absorption-dispersion of elastic waves in two-phase discrete (porous) media are briefly discussed. According to the models, the dissipation of body seismic waves in porous media is mainly explained by viscous friction at contacts of a solid rock matrix and a pore fluid. The friction occurs due to the fluid flow induced by a seismic wave propagation at different scales[1]. In the exploration seismic frequency band (5-150 Hz), the main contribution to the inelastic energy absorption is associated with the fluid flow at the mesoscale. The energy loss (absorption) at the mesoscale can be observed in the medium with heterogeneous fluid saturation (patchy saturation) or fracturing, in which the size of contrasting heterogeneities (gas bubbles, fractures) exceeds the pore size but is less than the wavelength. All mechanisms of the intrinsic wave energy absorption caused by the wave-induced fluid flow are characterized by a bell-shaped form of the dissipation factor (inverse quality factor), $Q_{\text{int}}^{-1}(\omega)$, versus frequency, ω. The maximum of the intrinsic absorption, $Q_{\text{int}}^{-1}(\omega_c)$, is observed at a characteristic frequency, ω_c, that depends on the orientation and geometric characteristics of the inhomogeneities [2]. In the exploration seismic frequency band, an increase of intrinsic dissipation factor, $Q_{\text{int}}^{-1}(\omega)$, with an increasing frequency, ω, is expected, which is confirmed by the experimental data [3]. Thus, the constant Q-factor model (frequency-independent Q) widely used in seismic exploration is not always sufficient for describing the inelastic absorption in real geological media.

Section 1.1 also provides phenomenological absorption-dispersion models, namely the Kolski-Futterman model, constant Q model[4], power law for absorption[5], 2nd and 3rd Azimi laws, power law for Q-factor (Muller model). According to these models, in the frequency band of the seismic exploration survey (5-150 Hz), the differences in the velocity dispersion, $c(\omega)$, are negligible and amount to the first

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[1] Kovtun A.A. About the equations of the Biot model and their modifications / A.A. Kovtun // Scientific notes of St. Petersburg State University. – 2011. – № 444. – P. 3-26 (In Russian)

[2] Müller T.M. Seismic wave attenuation and dispersion resulting from wave-induced flow in porous rocks — A review / T.M. Müller, B. Gurevich, M. Lebedev // Geophysics. – 2010. – V. 75. – № 5. – P. 75A147-75A164.

[3] The measurement of velocity dispersion and frequency-dependent intrinsic attenuation in sedimentary rocks / M. Sams [et al.] // Geophysics. – 1997. – V. 62. – № 5. – P. 1456-1464.

[4] Kjartansson E. Constant Q-wave propagation and attenuation / E. Kjartansson // Journal of Geophysical Research: Solid Earth. – 1979. – V. 84. – № B9. – P. 4737-4748.

[5] Strick E. The Determination of Q, Dynamic Viscosity and Transient Creep Curves from Wave Propagation Measurements / E. Strick // Geophysical Journal International. – 1967. – V. 13. – № 1-3. – P. 197-218.

percent. For amplitude attenuation, $\alpha(\omega)$, the differences can reach the first tens of percent between the models at certain frequencies. Determining a specific model from seismic data requires broadband observations and application of the robust frequency-dependent methods of attenuation analysis.

In real geological media, an additional contribution to the amplitude damping and seismic velocity dispersion is made by elastic wave scattering by contrasting microinhomogeneities, $Q_{scat}^{-1}(\omega)$. During the wave scattering, the total energy of the wave process is preserved and does not transfer to the heat as it does in the case of inelastic absorption. The wave scattering causes an apparent frequency-dependent attenuation of the transmitted waves and a complex interference pattern along the entire recording length.

Contrasting thin layers, the thickness of which is several times less than the wavelength, can also cause the elastic scattering of seismic waves. The scattering occurs due to the formation of intense internal multiple reflections in the stack of thin layers during the wave propagation. In *section 1.2*, the study of elastic scattering based on the generalized O'Doherty and Anstey (ODA) model for randomly layered media is presented. It has been shown that in the exploration seismic frequency band (5-150 Hz), noticeable elastic scattering of waves, $Q_{scat}^{-1}(\omega) > 0.005$, which corresponds to an intensity loss of more than 0.2 dB at a wavelength, is observed in thin-layered media, the contrast of which is characterized by a standard deviation of more than 10 % (Figure 1a).

The maximum elastic scattering in such media occurs at the frequency that depends on the characteristic thickness of contrast layers, a. For a signal with a spectrum of 5-150 Hz, scattering is observed in the media with characteristic thicknesses of contrast layers from 1 to 10 m (Figure 1b).

As a rule, in real geological media, contrasts of elastic properties between adjacent layers rarely exceed 30 %, which corresponds to reflection coefficients less than 0.2 on average (low-contrast media). However, some environments are characterized by a high contrast of elastic properties. One example of a contrasting environment is the upper section of the Carnarvon Basin (offshore Western Australia), represented by the thin interbedding of dense cemented carbonates and sandy-argillaceous deposits.

According to the well logging data, in the interval with the carbonates, the standard deviation of fluctuations of elastic properties is on the order of 15-18 % with the contrast of properties for some adjacent layers exceeding 100 %. In *section 1.2*, a method for estimating the scattering attenuation parameters based on numerical modelling of the full wavefield is proposed and implemented in the Carnarvon Basin. Quantitative estimates of the frequency-dependent attenuation caused by elastic scattering of waves on the stack of thin layers of the carbonate rocks are given. Typical values of quality-factor, Q_{scat}, that characterize the elastic scattering in the target area are from 60 to 110.

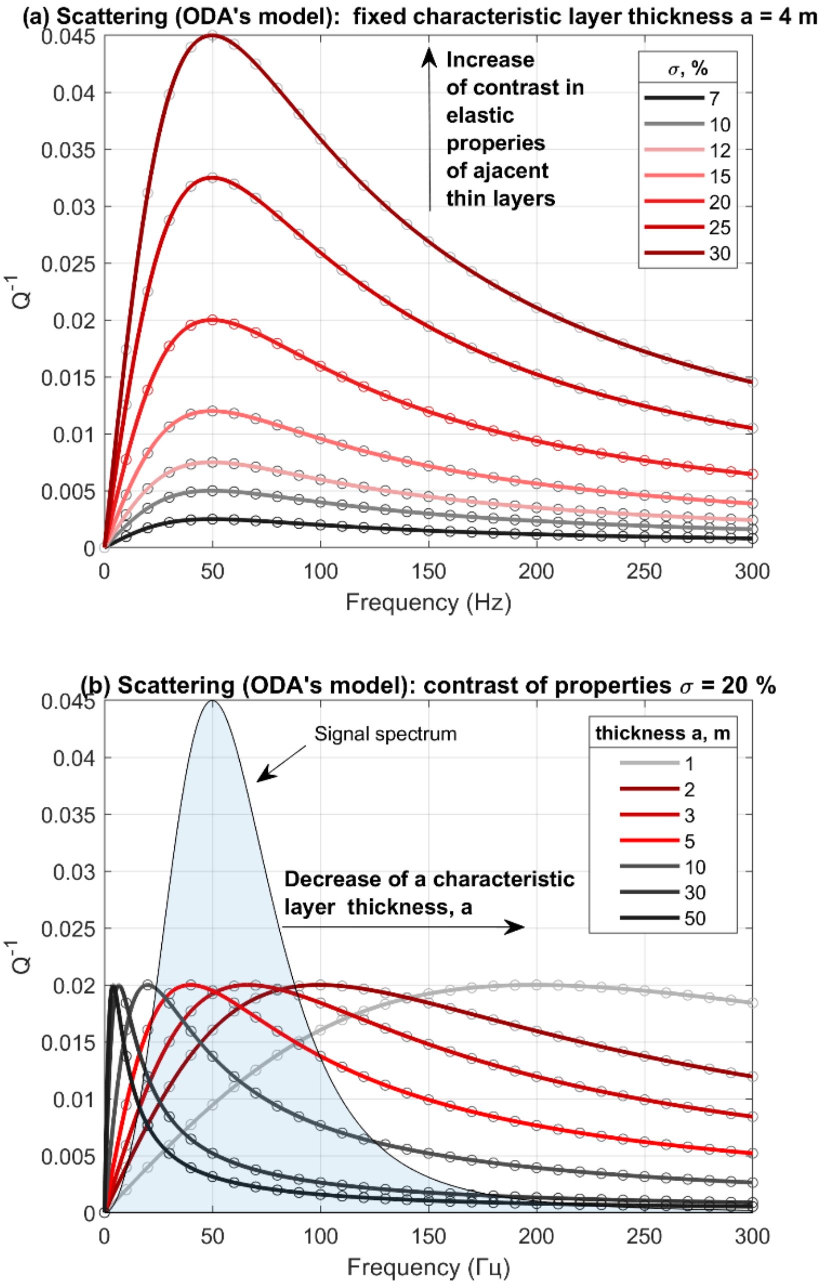

Figure 1. Scattering attenuation Q^{-1}_{scat} versus frequency (in Hz). Media with different acoustic contrasts, σ is from 7 to 30%; the characteristic thickness is fixed, $a = 4$ m, (a). Media with a characteristic layer thickness varying from 1 to 50 m; the model's contrast is fixed and characterized by $\sigma = 20\%$; blue colour shows a typical spectrum of a seismic signal, (b).

Chapter 2. Methods for estimation of frequency-dependent attenuation of seismic waves

Chapter 2 of the thesis provides a review and a comparative analysis of the modern approaches to estimating frequency-dependent attenuation of seismic waves. It is shown that all standard methods, including the spectral ratio method, the amplitude decay method, the analytical method, the centroid frequency shift method, the least-square optimization of spectra, assume that the inelastic medium is homogeneous (*section 2.2*). The assumption makes these methods sensitive to wave interference. Hence, it is impossible to separate the effects of inelastic absorption and elastic scattering of waves using these methods. The same conclusions apply to the Q-tomography based on the standard methods of Q-estimation, such as the spectral-ratio method (*section 2.3*).

An alternative approach to Q-estimation is the inversion of the seismic wavefield. The inversion allows one to account for wave interference through the wavefield modelling and, thereby, increase the resolution and the accuracy of the frequency-dependent attenuation estimates (*section 2.4*). Another advantage of the inversion approach is that it allows one to specify an arbitrary absorption-dispersion model. In contrast, almost all the standard methods (except for the spectra/signal optimization and the velocity dispersion analysis) are based on a constant quality-factor (Q) model.

Section 2.5 discusses approaches to the separation of elastic scattering and inelastic absorption phenomena from exploration seismic data. Traditionally, measurements of sonic and density well logs are utilized to estimate parameters of 1D elastic scattering either based on a theoretical model (e.g., ODA model) or based on a numerical wavefield modelling and estimation of Q-factors, which correspond to elastic scattering, from the synthetic wavefield using the standard methods of Q-estimation. There are several problems in the application of these two approaches in practice. In the first case, the assumptions of the theoretical model are not always fulfilled, such as, for example, the assumption on small fluctuations of elastic properties of the media. In the second case, the standard methods of Q-estimation operate unstably on small measuring bases and can give erroneous estimates of Q-factors due to the influence of wave interference in contrasting inhomogeneous media. It seems more promising to account for elastic scattering explicitly through the wavefield modelling in the inverse problem framework, which is the subject of this study.

Chapter 3. Waveform inversion of vertical seismic profiling data for estimation of frequency-dependent attenuation

The chapter develops a methodology for assessing the inelastic absorption of seismic waves in horizontally layered (vertically inhomogeneous) media. It is proposed to invert the wavefield recorded by vertical seismic profiling (VSP) in a borehole to estimate the absorption of seismic waves in the near-wellbore rocks. If the VSP is carried out in the borehole, well logging data are also available as a rule. The measurements of P-, S-wave velocities and densities (sonic and density logs) of rocks can be utilized to model the full wavefield in a horizontally layered medium. The typical resolution of the well logging data (0.1–0.15 m) allows the construction of highly detailed elastic models of vertically inhomogeneous media. By detailed, we mean models, the thickness of the layers of which is several times less than the wavelengths corresponding to the seismic frequency band (*section 1.2*). Refraction at boundaries, interference with reflected waves, and elastic scattering by vertical microinhomogeneities (thin layers) are explicitly taken into account in the wavefield simulated for such detailed models. Since the layer-induced (1D) scattering is incorporated through the full-wave modelling, the inversion has a natural ability to separate it from absorption estimates.

The use of well logging data for the full-wave modelling within the inversion framework allows, firstly, to get away from the classical assumption of the homogeneity of an inelastic medium when assessing the absorption parameters, and, secondly, to exclude the influence of elastic scattering, Q_{scat}^{-1}, on estimates of the intrinsic inelasticity of rocks, Q_{int}^{-1}. Within the modelling, an absorption-dispersion model can be specified, including one that assumes the frequency dependence of the inverse quality factor $Q_{int}^{-1}(\omega)$. If it is required to estimate effective attenuation parameters, Q_{eff}^{-1}, modelling for macro models, the layer thickness of which is several times greater than the wavelength (*section 1.2*), should be performed within the framework of the inversion procedure. Upscaling of the well logging data could be done using Backus averaging[6].

For the fast computation of the full wavefield in horizontally layered media it is convenient to use a matrix plane wave propagator[7]. *Section 3.1* describes the principles of the wavefield calculation using the matrix propagator method in a vertically inhomogeneous imperfectly acoustic (absorptive) medium[8]. The matrix propagator can be constructed for the general case of a plane wave incidence at an arbitrary angle in an elastic anisotropic medium[9]. This can be extended to an inelastic anisotropic medium using the exponential decay model by analogy with the propagator for the imperfectly acoustic medium.

Section 3.2 of the thesis provides a workflow for preprocessing of the borehole seismic data and the inversion methodology. In general, the application of the full waveform inversion requires minimal preprocessing. The preprocessing workflow consists of the following procedures:

1) 3C orientation of the VSP data;

2) quality control and removal of poor-quality seismic traces;

3) noise subtraction;

4) correction of amplitudes for the spherical wavefront divergence;

5) time-windowing near the first breaks.

It is not possible to compensate amplitudes of the entire wave package, including multiple reflections, for the wavefront divergence. To avoid errors in the inversion results caused by the undercompensated wavefront divergence, it is proposed to conduct the inversion of the full wavefield only near the first arrivals. According to the test results, the window size for temporal filtering should be about three pulse lengths.

The seismic trace for the k-th receiver can be represented as:

$$s_k(t) = s_o(t) * h_k(t) \times a_k, \qquad (2)$$

[6] Backus G.E. Long-Wave Elastic Anisotropy Produced by Horizontal Layering / G.E. Backus // J. Geophys. Res. – 1962. – V. 67. – № 11. – P. 4427-4440.

[7] Haskell N.A. The dispersion of surface waves on multilayered media / N.A. Haskell // Bulletin of the Seismological Society of America. – 1953. – V. 43. – № 1. – P. 17-34.

[8] Ganley D.C. A method for calculating synthetic seismograms which include the effects of absorption and dispersion / D.C. Ganley // Geophysics. – 1981. – V. 46. – № 8. – P. 1100-1107.

[9] Schoenberg M. “Zoeppritz” rationalized, and generalized to anisotropic media / M. Schoenberg, J. Protazio // The Journal of the Acoustical Society of America. – 1990. – V. 88. – № S1. – P. S46-S46.

where $s_o(t)$ – the source function; $h_k(t)$ – the transfer function of the geological medium that corresponds to the Fourier transform of the transfer function $H_k(\omega)$ computed in the frequency domain using a plane-wave matrix propagator approach given the available well logs and the absorption-dispersion model; a_k – the coefficient that characterizes coupling of the k-th geophone with the rock in the borehole. The coefficients a_k are unknown and are to be inverted simultaneously with the target attenuation parameters, Q_p^{-1}. To solve the nonlinear inversion problem, it is proposed to minimize the residual functional using the L_2-norm (a least-square method):

$$\| f(m) - d \|_2 \rightarrow \min \qquad (3)$$

where $f(m)$ – the forward modelling operator, m – the target model in the depth interval $[z_k\ z_{k+l}]$, $m = [Q_k^{-1}(\omega), a_k, ..., a_{k+1}]$; d – the recorded wavefield (observed data). In the proposed inversion framework, the model m is optimized using the simplex method[10]. Below is a general workflow of the proposed waveform VSP inversion in a sliding window (Figure 2).

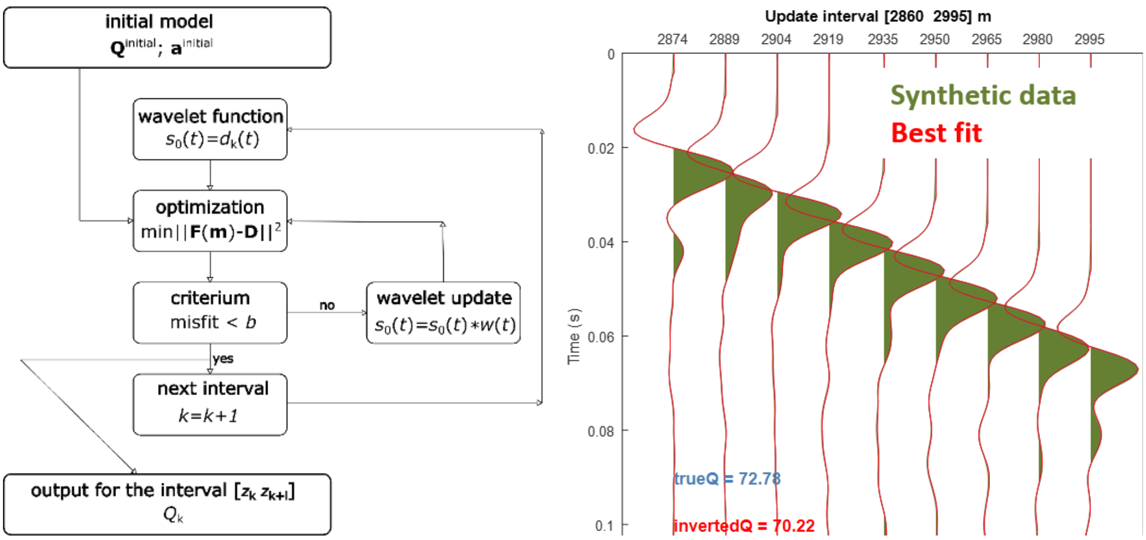

Figure 2. Workflow of the waveform inversion of the VSP data for estimation of frequency-dependent attenuation parameters (left). The example of the restored wavefield in the inversion interval (right).

[10] Sen M.K. Global Optimization Methods in Geophysical Inversion / M.K. Sen, P.L. Stoffa. – Cambridge: Cambridge University Press, 2013.

The first trace in the inversion interval is considered as the initial pulse estimate, $s_o(t)$. If the discrepancy between the observed and the restored wavefields is unsatisfactory, the source function is iteratively refined using the Wiener deconvolution, and the inversion is repeated until the threshold value of the residual is reached.

Section 3.3 presents the synthetic study of the inversion applicability and its comparison with the standard spectral ratio method. The synthetic dataset was generated as follows. A layered model of a medium with a known scattering function was set, $Q^{-1}_{scat}(\omega)$. The inelastic absorption and dispersion for each layer were set according to the Kolski-Futterman model, $Q_{int} = 60$. The attenuation model and the corresponding synthetic field are shown in the figure (Figure 3).

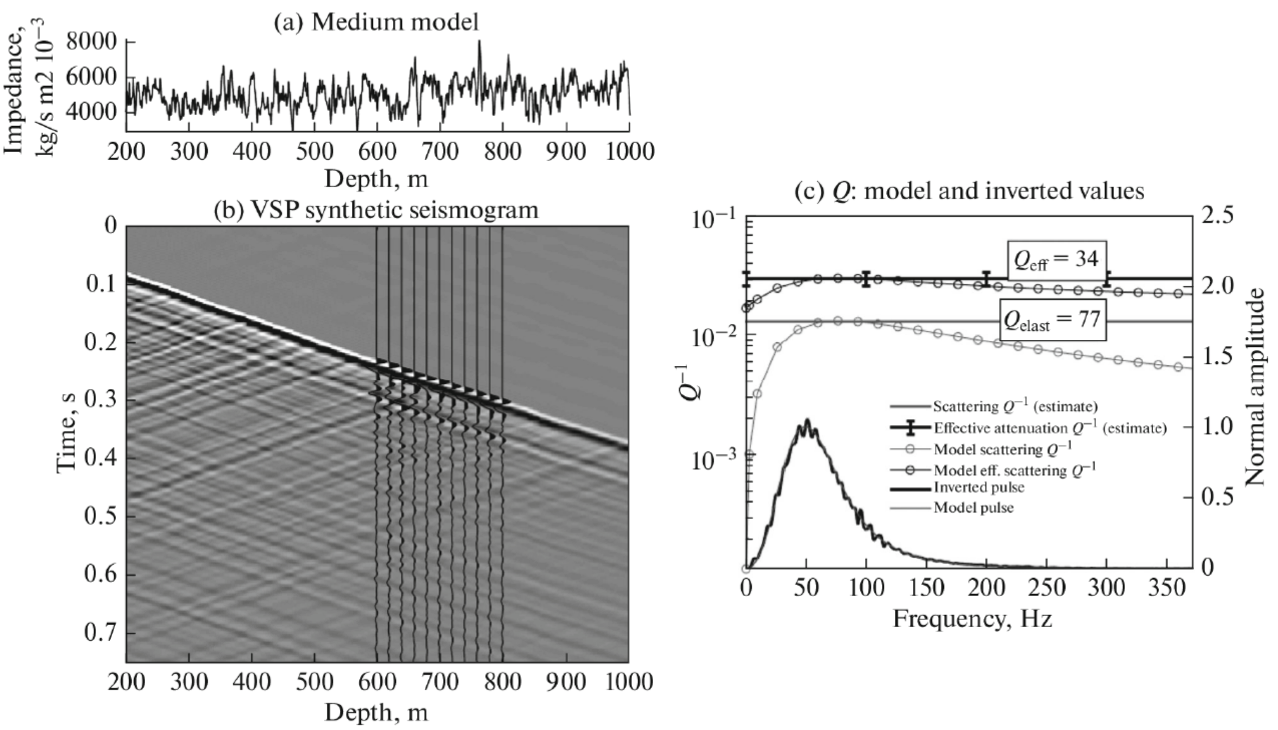

Figure 3. The acoustic model of the medium, (a). The synthetic VSP seismogram overlayed with the traces utilized in the inverison in the depth interval 600-800 m, (b). The attenuation model of the medium (round marker) and the inverted attenuation model (solid line), (c).

The inversion was carried out in a 200 m window in two stages. Before the inversion, random noise of the order of 10 % was added to the synthetic data. At the first stage, to estimate the effective attenuation Q^{-1}_{eff}, the wavefield within the forward modelling was calculated for the macro model, the thickness of the layers of which was more than 10 m. To assess the influence of a model averaging base on the estimation of effective attenuation, Q^{-1}_{eff}, tests were performed with the averaging bases of 10 m, 15 m, 50 m. At the second stage, the wavefield simulation was carried out for a thin-layered model using the averaging base of 1 m to account for elastic scattering in a layered medium and estimate, respectively, the inelastic absorption parameter, Q^{-1}_{int}.

The estimated attenuation models and the spectrum of the inverted pulse are shown in the figure (Figure 3c). According to the results of the tests with different averaging bases, the confidence interval for assessing the effective attenuation parameter was about 6 %, $Q_{\text{eff}} = 34 \pm 2$. Inelastic absorption is determined with high accuracy, $Q_{\text{int}} = 60$, making it possible to reliably estimate the maximum of the elastic scattering, $Q_{\text{scat}} = 77$.

Under the same conditions (the analysis window is 200 m, the pulse is determined from the data), the spectral ratio (SR) method gives an error in the estimate of the effective attenuation, Q_{eff}, on the order of 35 %. Moreover, the estimate strongly depends on the selected frequency band. This instability of the estimates by the SR method is due to its assumption on the homogeneity of the inelastic medium. In practice, the geological medium is inhomogeneous, which results in the presence of multiple reflections in the seismic data. The signal of the direct wave is usually distorted by wave interference, which causes fluctuations in the spectrum. On small measurement bases, this leads to significant errors in the estimation of attenuation by standard methods such as the SR method.

Section 3.4 presents the results of the inversion application to the field borehole seismic data. In the North West Shelf of Australia in the Wheatstone field, the *A Sand (Z90)* reservoir of the *Mungaroo* formation was identified based on the inverted absorption estimates. It is noteworthy that the *Mungaroo A Sand (Z90)* reservoir cannot be distinguished from the embedding non-reservoir formations by acoustic impedance. A joint analysis of the Q-factors characterizing the absorption in the medium and the acoustic properties makes it possible to distinguish a gas-saturated reservoir with a thickness of about 60 m from the surrounding non-productive rocks.

In the Cooper Basin (Australia) the survey area, it is shown that in the *Patchwarra* reservoir characterized by high-contrast interlayering of coal seams, the apparent frequency-dependent attenuation, $Q^{-1}_{eff} = 0.12 \pm 0.02$, is mainly caused by scattering of seismic waves (Figure 4b). The synthetic VSP seismogram calculated for the elastic thin-layered model fully explains the observed wavefield that proves the conclusion on the scattering nature of the observed apparent frequency-dependent attenuation (Figure 5).

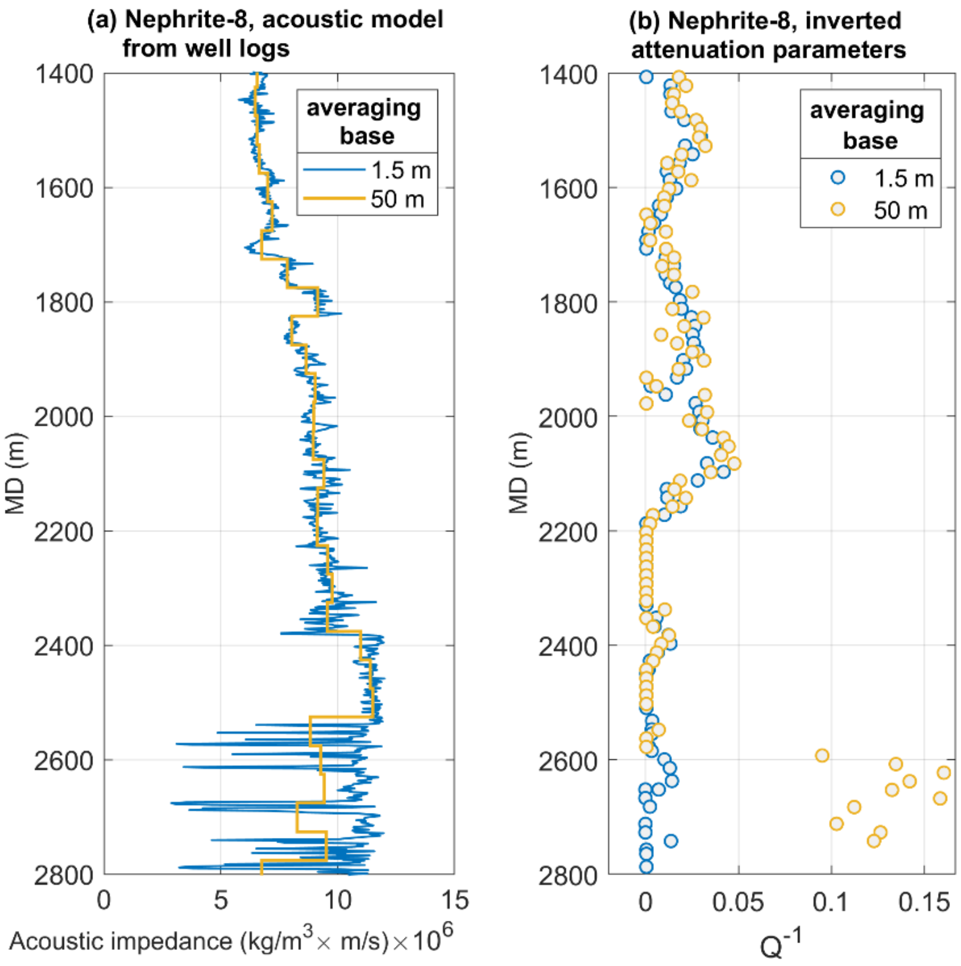

Figure 4. The models of acoustic impedance computed from the well logs and averaged using the averaging bases of 1.5 m (blue line) and 50 m (yellow line), (a); the inverted models of absorption (blue marker) and apparent (effective) attenuation (yellow marker), (b).

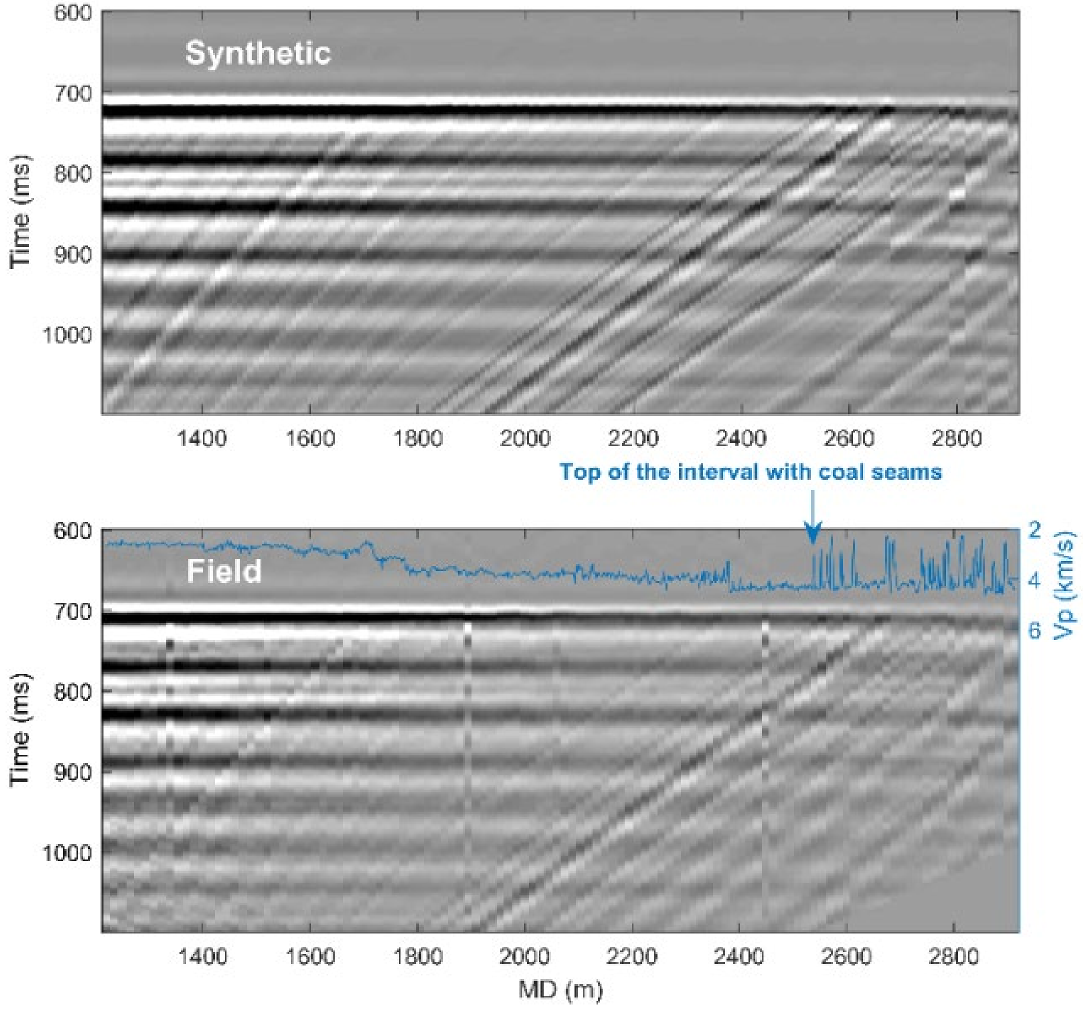

Figure 5. The synthetic VSP seismogram, (a), and the field VSP seismogram overlayed with sonic log (P-wave velocity measurements), (b).

Chapter 4. Study of frequency-dependent attenuation of seismic waves at the Otway CO2CRC research site for geosequestration and monitoring of carbon dioxide CO_2

The final chapter presents the results of a comprehensive study of frequency-dependent seismic attenuation at the Otway research site (Victoria, Australia) for storage and monitoring of the CO_2 in the subsurface.

At the Otway site, one-dimensional waveform inversion appeared to be a more reliable method for estimating frequency-dependent attenuation than the amplitude decay method and the centroid frequency shift (CFS) method. The inversion is less sensitive to the presence of noise and variable seismic excitation parameters. The inverted attenuation parameters estimated in one well from the VSP datasets obtained with different seismic sources are entirely consistent. At the same time, the attenuation estimates by the standard methods depend on the selected frequency band and the pulse estimate.

However, both the standard methods and the 1D waveform inversion incorrectly estimate frequency-dependent attenuation in the depth intervals, where the subsurface structure differs significantly from the horizontally layered model. At the Otway site, the attenuation estimates are distorted by the influence of sub-vertical faults located in the vicinity of the boreholes. One indicator of the unreliable attenuation estimate can be the inconsistent behavior of the amplitude decay and the centroid frequency decay curves in the studied interval. In the case of inversion, the criterion of unreliability is the large value of the residual.

Injection of 15 000 tons of a carbon dioxide and methane mixture CO_2/CH_4 to the depth of ~ 1.5 km into a thin sandy layer 15 m thick does not cause a visible change in the spectral characteristics of the seismic signal. According to the theoretical model of absorption for porous fluid-saturated media, the thickness of the CO_2/CH_4 plume must exceed 50 m to cause noticeable absorption of seismic energy (intrinsic attenuation) in the seismic frequency band.

Conclusion

In the thesis, the study of elastic scattering of seismic waves in vertically inhomogeneous contrasting media is carried out based on the numerical full wavefield modelling and the theoretical models. The parameters of the layered media (the characteristic layer thicknesses, the contrast of elastic properties of adjacent thin layers) that cause frequency-dependent attenuation of propagating seismic waves have been determined. In the North West shelf of Australia, the influence of contrasting thin-layered carbonate rocks on the quality of seismic reflection images is shown. Estimates of the Q-factors that characterize the elastic scattering of seismic waves in the area are given.

Based on the literature review and own research, it is shown that the standard methods for estimating frequency-dependent seismic attenuation, including the spectral ratio method and the centroid frequency shift method, are sensitive to fluctuations in the spectrum caused by the wave interference. An alternative approach to the estimation of seismic attenuation is a waveform inversion that can explicitly model interference of seismic waves and allow for more complex attenuation-dispersion relations rather than constant Q (quality-factor) model.

In the thesis, a new robust approach to the estimation of dissipation factors Q^{-1} is developed using the waveform inversion of VSP and well log data. When the high-resolution well logs are available, interference and multiple scattering by a stack of thin layers can be modelled explicitly without any assumptions on the statistical distribution of the vertical inhomogeneities. The waveform inversion utilizes this approach in its forward modelling. Since the layer-induced (1D) scattering is incorporated through the full-wave modelling, the inversion has a natural ability to separate it from absorption (intrinsic attenuation) estimates.

Synthetic and field applications of the developed waveform inversion prove that it can separate intrinsic from scattering attenuation parameters in horizontally layered subsurface. Besides, the waveform inversion appears to be more robust and reliable for Q-estimation in small depth windows (< 75 m) than conventional methods such as amplitude decay, spectral ratio, and centroid frequency shift methods. The limitations of the inversion are that it requires good quality sonic (and ideally, density) logs and only incorporates 1D scattering.

The developed waveform inversion technique for estimation of inelastic absorption of seismic waves contributes to the development of quantitative interpretation methods, which are the basis for predicting reservoir properties in the interwell space.

Key publications

[1] **Pirogova A.** Multiwell study of seismic attenuation at the CO2CRC Otway project geosequestration site: Comparison of amplitude decay, centroid frequency shift and 1D waveform inversion methods / A. Pirogova, R. Pevzner, B. Gurevich, S. Glubokovskikh, K. Tertyshnikov // Geophysical Prospecting. – 2019. – V. 67. – № 7. – P. 1778-1797.

[2] **Pirogova A**. Separation of frequency-dependent scattering and inelastic absorption by waveform inversion of VSP data constrained by well logs // Moscow University Geology Bulletin. – 2019. – V. 74. – № 5. – P. 521–524

[3] **Pirogova A**. Effect of finely-layered stiff carbonates on a seismic response. Northern Carnarvon basin synthetic study / A. Pirogova, R. Pevzner, B. Gurevich, S. Vlasov // ASEG Extended Abstracts. – 2018a. – T. 2018. – № 1. – P. 1-6.

[4] **Pirogova A.** Multi-well study of seismic attenuation at the CO2CRC Otway Project geosequestration site / A. Pirogova, R. Pevzner, B. Gurevich, S. Glubokovskikh, K. Tertyshnikov // Extended Abstracts of 80th EAGE Conference and Exhibition 2018. – EAGE, 2018b.

[5] **Pirogova A.** Study of intrinsic versus scattering attenuation of seismic waves from borehole measurements / A. Pirogova, B. Gurevich, R. Pevzner, S. Vlasov // SEG Technical Program Expanded Abstracts 2018. – 2018c. – P. 5387-5391.

[6] **Pirogova A.** Estimation of intrinsic Q in finely-layered media by wavefield inversion of VSP Data - Australian North West Shelf case-study / A. Pirogova, B. Gurevich, R. Pevzner, S. Glubokovskikh // 79th EAGE Conference and Exhibition 2017. – EAGE Publications BV, 2017a.

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[9] Puzyrev V. Seismic Inversion with Deep Neural Networks: a Feasibility Analysis / V. Puzyrev, A. Egorov, **A. Pirogova**, C. Elders, C. Otto // Extended abstracts of 81st EAGE Conference and Exhibition 2019. – EAGE, 2019.