MINISTRY OF EDUCATION AND SCIENCE OF THE REPUBLIC OF KAZAKHSTAN

Kazakh National Research Technical University named after K.I.Satpayev

Institute of Geology, Oil and Mining

Department of Oil, Gas and Ore Geophysics

Issagali Assem Aidarkyzy

Topic: “Information content of seismic inversion in the search for oil and gas deposits”.

DIPLOMA WORK

Specialty 5B070600 – Geology and exploration of mineral deposits

Almaty 2020

MINISTRY OF EDUCATION AND SCIENCE OF THE REPUBLIC OF KAZAKHSTAN

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K. Turysov Institute of Geology, Oil and Mining

Department of Oil, Gas, and Ore Geophysics

ADMITTED TO DEFENCE
Head of the Department of Geophysics
Doctor of geological-mineralogical sciences, professor
Abetov A.E.
“_____”_______________2020y.

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Done by Issagali A. A.

Scientific superviser

Doctor Ph.D.

Umirova G. K.

“_____”________2020 y.

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Geophysics Department

APPROVED BY
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THE TASK
to complete the diploma work

Student Issagali A. A.

Topic: « Information content of seismic inversion in the search for oil and gas deposits »

Approved by order of the Rector of the University №762–b from "27" January 2020 y.

Submission deadline of the completed work "15" May 2020 y.

Initial data for the diploma work: were provided by the scientific adviser

Summary of the diploma work:

a) Current state of seismic inversion development;

b) Theoretical bases of seismic inversion;

c) Methods of seismic inversion and examples of some results;

List of graphic material: 24 slides of the presentation of work are presented. Recommended main literature: Kondratyev I.K., Ryzhkov V.I., Kissii Yu.M., Shubin A.V. Ways of Implementation and Efficiency Assessment of Seismic Inversion.

GRAPH
of diploma work preparation

Name of sections, list of issues to be developed	Submission deadline to scientific adviser	Notation
Current state of seismic inversion development	8.03.20y.-29.03.20y.	
Theoretical bases of seismic inversion	1.04.20y.-9.04.20y.	
Methods of seismic inversion and examples of some results	10.04.20y.-11.05.20y.	

Signatures
consultanыts and the standard controller for the finished diploma work indicating the sections of work related to them

Name of sections	Consultants, N.P.F. (academic degree, rank)	Date of signature	Signatures
Current state of seismic inversion development	G. K. Umirova		
Theoretical bases of seismic inversion	G. K. Umirova		
Methods of seismic inversion and examples of some results	G. K. Umirova		
Standard controller	M.M.Aliakbar		

Scientific supervisor Umirova G. K.

Students fulfilling the task ____________________ Issagali A. A.

Date "_____"_______________2020 y.

АҢДАТПА

Дипломдық жұмысқа "Мұнай-газ шоғырларын іздеу кезіндегі сейсмикалық инверсияның ақпараттылығы"

Жұмыс кіріспеден, 4 тараудан, қорытындыдан, пайдаланылған әдебиеттер тізімінен және 25 қосымшадан тұрады.

Дипломдық жұмыста геологиялық барлау жұмыстарының қазіргі кезеңі сипатталған және мұнай-газ перспективалы объектілерді бөлу кезінде өзін жақсы көрсеткен әдістерді қолдану қажеттілігі негізделген. Басып шығарылған және қор әдебиеттерін шолу негізінде сейсмикалық инверсияның артықшылықтары жазылды, ол өнімді қабаттардың түрлі петрофизикалық параметрлерінің көлемді таралуын болжамдау кезінде міндеттердің кең ауқымын шешеді. Әрбір алгоритмнің қысқаша сипаттамасымен сейсмикалық амплитудалық инверсиясының алгоритмдері жіктелді. Сейсмикалық инверсия есептерінде қолданылатын математикалық әдістерге жалпылау жасалды.

Нақты мұнай-газ кен орны мысалында мұнай-газ объектілерін іздеу және олардың сүзу-сыйымдылық қасиеттерін анықтау кезінде акустикалық инверсияның ақпараттылығы зерттелді.

АННОТАЦИЯ

К дипломной работе “Информативность сейсмической инверсии при поисках нефтегазовых залежей”

Дипломная работа состоит из введения, 4 глав, заключения, списка использованной литературы и 25-ти приложений.

В данной дипломной работе охарактеризован современный этап геологоразведочных работ и обоснована необходимость использования методов, хорошо зарекомендовавших себя при выделении нефтегазоперспективных объектов. На основе обзора изданной и фондовой литературы выделены достоинства сейсмической инверсии, решающей широкий круг задач при прогнозе объемного распределения различных петрофизических параметров продуктивных пластов. Сформирована классификация алгоритмов амплитудной инверсии сейсмических данных с кратким описанием каждого алгоритма. Сделано обобщение математических методов, используемых в задачах сейсмической инверсии.

На примере конкретного нефтегазового месторождения исследована информативность акустической инверсии при поисках нефтегазовых объектов и определении их фильтрационно-емкостных свойств.

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ABSTRACT

Diploma work "Information content of seismic inversion in the search for oil and gas deposits"

The graduation work consists of an introduction, 4 chapters, conclusion, list of used literature and 25 attachments.

The following diploma work describes the modern stage of geological exploration and substantiates the need to use methods that have proven themselves in the identification of oil and gas prospective objects. On the basis of a review of published and stock literature, the advantages of seismic inversion have been identified, which solves a wide range of problems in predicting the volume distribution of various petrophysical parameters of productive formations. Was formed a classification of the algorithms for amplitude inversion of seismic data with a brief description of each algorithm. A generalization of the mathematical methods used in seismic inversion problems was performed.

On the example of a specific oil and gas deposit, was investigated the information content of acoustic inversion in the search for oil and gas objects and the determination of their filtration-capacitive properties.

CONTENT

INTRODUCTION

One of the most important conditions for carrying out of the new Code of the Republic of Kazakhstan "on subsoil and subsoil use" is to provide categorical oil and gas reserves. Kazakhstan is one of the largest oil producing countries in the world. Oil in Kazakhstan began to produce in the late XIX century, much earlier , than in Iran , Kuwait , Mexico , Norway , Saudi Arabia . On results of 2017 the Minister of National Economy T. Suleimenov announced a record volume of oil production in the history of Kazakhstan- 86.2 million tons. Therefore, modern conditions require a sharp expansion of exploration to realize the resource potential of the Republic of Kazakhstan on a modern scientific - methodological basis.

The current stage of exploration is characterized by an increase in the complexity of the tasks of predicting oil and gas deposits, against the background of the requirement to reduce the cost of exploration. These include the complexity of reservoir distribution and high variability of the geological section, increasing the depth of productive horizons and low efficiency of geophysical work, the transition of the field to the" Mature " stage of development and its depletion. A significant increase in reserves can be achieved within significantly developed fields due to the discovery of small complex deposits. Therefore, this implies the need to improve existing and create new methods for identifying oil and gas potential objects.

Today, it is customary to complete each of the stages of the exploration process by creating a model of a reservoir containing hydrocarbon raw materials. The detail of the model and the completeness of the description of its physical and geological properties increase with the collection of geological and geophysical data from the regional stage of research to the exploitation of oil and gas deposits. The model of a geological object (reservoir) is the result of an integrated interpretation of data from a complex of geological and geophysical methods, and the reliability of the model determines success in solving the problem of predicting the capacitive characteristics of hydrocarbon deposits.

In the examples the most effective and successful prediction reservoir properties in almost all oil and gas basins of the Republic of Kazakhstan, 3D seismic exploration traditionally plays a leading role. The capabilities of the seismic research method in creating models of oil and gas deposits have significantly expanded, thanks to recently developed technologies for predicting reservoir capacity properties. These include all kinds of possible transformations of wave sections into various physical parameters of the environment (impedance, velocity). This class of transformations called seismic inversion, and today this procedure allows quite successfully predict reservoir properties of sedimentary complexes.

Thus, the development of a scientifically based methodology for predicting complex reservoirs, including non-anticline hydrocarbon traps with the identification of reservoir lithology, their saturation and productivity based on the use of inversion, is an urgent task.

Seismic inversion over the past decade has become one of the most popular tools for quantitative interpretation of seismic data. And if earlier inversion called the most diverse, variety of algorithms for obtaining various environmental properties from seismic data, now this concept has become more specific. Today, inversion is a certain class of numerical tasks with the help of extract information about the main elastic parameters of the medium — acoustic, shear impedance, and density, which extracted from a seismic record.

The purpose of this research is the study of information content of the inversion in the search for oil and gas traps and further determine their filtration and capacitance properties.

1 Current state of seismic inversion development

Due to its high energy intensity and transportability, since the 20th century, oil has been the most important energy source in the world. Today, up to 84 percent of the total amount of raw materials produced is used for fuel production. The other 16 percent are processed into plastics, solvents, fertilizers, medicines and other products without which modern civilization cannot see its existence.

To ensure the increase of hydrocarbon reserves (HC) in the middle of the twentieth century, the main attention was concentrated on the search for large fields containing large reservoirs, which are reservoirs for oil and gas accumulations, the thickness of which was tens or even hundreds of meters. At the moment, the discovery of hydrocarbon deposits of this type is becoming very rare. The main growth of reserves is due to medium and small deposits with shallow thickness of these reservoirs usually vary from units to 20 meters. Resulting in this situation, there is a need to improve and create new methods of searching for oil and gas deposits.

Seismic survey is one of the key areas in geophysics, intended to identify the boundaries of layers and study the properties of reservoirs.

In this case, the prediction of the reservoir parameters in the form of a record of reflected waves is one of the most difficult problems, the theoretical basis for the solution of which was founded in the early twentieth century by the work of English physicist Raleigh J.P. on the study of elastic wave propagation in a layered medium. In the 50-70s, Russian mathematicians and geophysicists Brehavek L.M., Petraten G.I., Alekseev A.S., Bereon I.S. and others made a great contribution to the development of this area.

The appearance of the computer has created conditions for a practical solution to predict the parameters of reservoirs in the form of recording reflected waves. It should be noted that the first creators and researchers of deconvolution (Robinson E.A., Kuletz G., Rice R.B., Treitel S.) considered this method as a way to determine the acoustic parameters of thin layers.

The most serious attempt at practical realization of such a method was made by I.K. Kondratyev et al. in the late 60s [1]. As a result of special experimental and methodological works, including the registration of reflections by large area groups and the use of a deeply sounded tube to determine the shape of the falling wave, the results of high-precision deconvolution of seismic traces restored detailed acoustic models of the environment. Comparing the results of the experiment with acoustic logging (AL) data of existing wells showed the success of the proposed method, but at that time the geophysicist was not ready for extensive use of labor-intensive field methods.

The creation of the first practical methods for solving the inverse dynamic seismic survey problem for a one-dimensional model of the medium containing thin layers with plane-parallel interface boundaries began with the use of acoustic inversion in the 80s of the last century. Russian geophysicists Rudyaitskaya D.I., Dubrovsky Z.M., Rudenko G.E., Kondratyev I.K., Skarnyakova E.G. were among the first in the world who developed original systems of acoustic inversion and implemented them in geophysical research practice. Now these systems have been improved and are now the primary tool for reservoir forecasting.

At the end of 80s - middle of 90s there began intensive work on creation of practical methods of seismic inversion for two-dimensional model of environment. Today these algorithms are called AVO-analysis or elastic inversion. Foreign geophysicists who were among the first to begin work on the creation of elastic inversion methods: Lortzer G.J.M., Berkhout A.J., Tarantola A., Hampson D., Russel V., Dahl T., Ursin V., Buland A., Ornre N. and others.

At present, the tasks of forecasting natural oil and gas reservoirs are solved with the use of a large arsenal of technical and software tools, accumulated considerable experience in field registration, processing and interpretation of 3D seismic data.

During the last decade a lot of works have appeared in the domestic and foreign literature, which demonstrate successful practical application of seismic inversion methods in different states. However, despite the widespread use of these methods around the world, very few studies have been published to date to obtain quantitative estimates of the accuracy and resolution of seismic inversion. These questions are considered most thoroughly and deeply in the works of VanRiel R., BerkhoutA.J., 1985 [2], Russell, V. And Hampson, D., 1991 [3], Kondratyev I.K., Lisitsyna, P.A., Kiseina, Y.M., 2005 [3], Levyanta, V.B. et al., 2006 [4], Gogonenkova, G.N., Fedosova, A.I., 2007 [5], Ampuva, Y. 2009 [6]

Seismic data can be research and interpreted on their own without inversion, but this does not allow to obtain the most detailed idea of the structure of the subsoil, and under certain conditions it can even lead to an unreliable result. Due to the efficiency and quality of seismic inversion, at present, most oil and gas producers use inversion technologies in order to increase the resolution and reliability of the data, as well as to improve the quality of rock properties, including porosity and oil-saturated thickness.

2 Theoretical bases of seismic inversion

Seismic inversion is one of the directions of quantitative interpretation of seismic data, which is based on mathematical approaches to solving the inverse dynamic tasks.

Seismic inversion is the process of converting seismic data into a quantitative description of the properties of the rocks composing the reservoir. At the same time, the purpose of inversion is to convert the wave representation of seismic records into a layered form, which is characteristic for geological sections. Seismic survey restores the properties of layers with thicknesses of about 8 meters of effective thickness or 32 meters of total thickness. In other words, the wave representation of reflections describes the behavior of reflection coefficients, i.e. the difference in properties at the boundaries of the seismic survey and does not distinguish thin interlayers and layers. Inversion is used to switch to the layer description.

The seismic inversion is capable of estimating the physical parameters of thin layers of the geological section by sections and P-wave seismograms. Physical parameters include: acoustic impedance Ip and time value ΔT (acoustic inversion); longitudinal Vp and transverse Vs wave velocities or impedances Ip, Is; and p density (elastic inversion). In the presence of a sufficient number of wells in the study area are established experimental dependencies (usually by creating cross-splots) between the physical and required to solve practical problems of geological parameters or properties of the reservoirs (effective power of reservoirs, porosity coefficients Cp, rock lithology, the nature of fluid saturation, etc.). In practice, to predict geological parameters besides physical parameters, additionally attracted dynamic attributes of the wave field (amplitudes, various parameters of frequency characteristics of reflections, etc.)

Inversion by its name can be considered a process inverse to the solution of a direct problem, sometimes called simply modeling. The solution of the direct problem begins with constructing a model of the properties of the geological environment; then, on this model make mathematical simulation of a physical experiment or process, for example, electromagnetic, acoustic, nuclear, chemical or optical, is carried out, and as a result, a model response is obtained. If the model and assumptions are accurate enough, this response is very close to real data. The inversion consists in the opposite: an operation is applied to the actually measured data, which, through the same physical experiment, leads back to obtaining a model of the geological environment. With the right inversion, this model should be similar to the real geological environment which we research.

2.1 Components, models and tasks of inversion

Components of inversion. The practical implementation of the inversion is impossible without using both seismic and down hole data. Seismic data have a limited bandwidth, which reduces seismic resolution and quality. In order to extend the existing frequency range, to obtain low frequency components, logging data, pre stack time or depth migration rates and/or regional gradients are used. Well logging results are used to add a low-frequency component outside the seismic band and impose limits on the inversion result. First, the well logging curves are processed and edited to ensure that there is an appropriate relationship between the impedance curves and the required physical properties of the rocks. The curves are then converted to a time domain, filtered to match the seismic bandwidth, introduced corrections for the impact of the wellbore , balanced and classified by quality.

Impulse estimation - all modern seismic inversion techniques require seismic data and an impulse estimated from these data. As a rule, the path of reflection coefficients along the well within the boundaries of seismic surveys is used to estimate the phase and frequency of the pulse. Accurate impulse estimation is very important for the successful realization of any inversion. The assumed shape of the seismic pulse can significantly affect the result of seismic inversion and, consequently, the subsequent assessment of the reservoir's filtration and capacity properties.

The amplitude and phase spectrum of the impulse are statistically estimated either by only seismic data or by seismic data when correlated with borehole data using wells with acoustic and density logging. The resulting seismic pulse will in turn be used to estimate the seismic reflection coefficients in the process of seismic inversion.

If the estimated (constant) phase of the statistical impulse is consistent with the final result, the process of estimating the impulse converges faster than in the case of the assumption of a “zero phase”. Minor editing and the 'stretch and compress' procedure can be used to better align the common-mode axes. Accurate impulse estimation requires an exact fit of the impedance curve to seismic data. Errors in linking to wells can lead to phase or frequency distortions in the impulse estimation.

After when the impulse is determined, a synthetic curve is calculated for each seismic trace. To ensure better quality, the result of inversion convolve with a impulse to obtain synthetic seismic traces, which compared with the original seismic trace.

Seismic inversion is a technology that allows using physically and mathematically based algorithms to use seismic data to predict the volume distribution of various petrophysical parameters of productive formations in the inter-well space.

Models. Two types of models are used in seismic inversion tasks, which differ in the level of detail: thin layered and layered.

Thin layered models. When working in the time domain, these are equidistant models with the time thickness of layers equal to the discreteness interval Δt (usually 2 millisecond). When performing inversion on a depth scale, the minimum layer thickness for such models approximately corresponds to their analogue-time domain (usually 3-4 meter).

Layered models. The second type of models will be called layer models. In the time domain, they are not equidistant, and the boundaries of the layers on the axis t are, if possible, timed to sharp changes in acoustic parameters. The minimum time power of the layers " t_{min} is determined by the actual resolution of the seismic survey. Usually for medium-frequency seismic survey " t_{min} = 6 millisecond, which corresponds to the minimum thickness of the layers 10-15 meter.

Tasks of inversion. Different types of seismic inversion solve a wide range of problems determined both by the goals of dynamic interpretation and seismic and geological conditions of the studied sediments, as well as by the availability of the necessary set of seismic and well data.

The efficiency of seismic inversion depends on the quality and completeness of the initial geological and geophysical data; geological features of the structure of the studied sediments; availability of preconditions for the separation of rocks by reservoir quality, lithology, saturation in the field of elastic parameters.

Tasks of inversion:

Determining acoustic parameters of thin layers. Obtaining of reliable distribution of elastic properties in the studied layered environment. Forecast of porosity and gas saturation distribution of productive reservoirs. Inversion is used for precise determination of drilling points, mapping of water saturation, improvement of hydrodynamic modeling quality and obtaining more accurate information.

Elastic properties obtained as a result of seismic inversion are used to assess and predict various properties ranging from the porosity of terrigenous reservoirs to the geomechanical properties of bituminous clays and fractured carbonates.

3 Overview of seismic data inversion methods

To solve various types of problems, specialists of seismic exploration use different types of inversion: **velocity** and **dynamic (amplitude).**

Velocity inversion, sometimes also called travel time inversion, is used for deep constructions. In this case, along seismic trace at points located with a large interval, a deep-speed model is obtained that is consistent with the recorded travel times of the seismic waves. This relatively crude model spans the environment a few kilometers in depth and possibly hundreds of kilometers in length and width. This solution is used at different stages of data processing, for example, during migration and summation, resulting in a seismic image that is familiar to most readers. Seismic data interpreters use these images to determine the geometry and depth of reflecting horizons.

Inversion of the second type is dynamic. With this inversion, the arrival time and the amplitude of the reflected seismic waves at each reflection point are used to determine the relative impedances of the layers between the selected reflecting boundaries. Thus, this inversion, called “seismic inversion to describe the layers”, provides information contained, figuratively speaking, “between the lines” - between these reflecting boundaries. This information is required to obtain detailed models of rock properties.

Intensive development of the dynamic interpretation direction in seismic exploration has led to the appearance of various algorithms of seismic inversion, which differ in mathematical approaches and accuracy in solving the geological problems, but are united by one purpose - to obtain a reliable distribution of elastic properties in the studied layered medium.

The main purpose of seismic data inversion is to restore the acoustic and elastic properties of rocks, which can be connected through effective models of mediums with reservoir properties (lithology, porosity, saturation character) or with physical conditions (pressure, temperature) under which they are located [7].

There are many different inversion technologies, they are can be divided into two sets of categories: first, based on implementation - inversion pre or post stack, and second, inversion with resolution of seismic data or resolution of logging data. The combination of these categories allows you to get four technical approaches to solving the inversion problem, and the choice of a certain type of inversion in each case depends on the tasks and the characteristics of the rocks. Despite the fact that the presented order reflects the development of inversion technologies over the past 20 years, each category finds its effective application in the implementation of individual projects or as part of a larger work graph.

3.1 Mathematical methods used in seismic inversion

The inversion tasks can be presented as follows [8]. Imagine that there is a theoretical model *A*, which connects (linearly or nonlinearly) model parameters *m* and data *d*. Let us denote the observed data by *dobs,* and the synthetic data *dcalc* - obtained by solving the direct problem on the given model. The purpose of the inversion is to find model m parameters that minimize the function (target function) of the difference between *dobs* and *dcalc*. The discrepancies arise because we do not know the true model parameters, the model has a simplified reality representation and the measured data contain noise. Target functions include not only the *dobs* and *dcalc* inconsistency, but also constraints derived from a priori data and smooth solution conditions. Different mathematical methods can be used to solve the minimization problem: LSM, gradient descent methods, linear programming, simulation anniling, random search methods (Monte Carlo method), neural network and genetic algorithms. A probabilistic approach can also be used to solve inversion problems.

Linear method (LSM)

In this case the data and the model are connected linearly and the expression in the matrix form can be written down:

$$\mathrm{Am} = \mathrm{d} \tag{1}$$

The solution of this type of equation was obtained using the least squares method (LSM):

$$m = (A^T A)^{-1} A^T d_{obs} \tag{2}$$

This method is used to find ASO attributes: lntercept and Gradient from the linearized 2-member Shue’s approximation.

Gradient descent methods

These are numerical methods that solve a nonlinear linearization problem around the initial approximation. At each iteration the model is updated and iterations stop when the iteration criterion is reached of minimization. Examples of this method for solving the inversion problem are: Newton's method and the conjugate gradient method [9].

Simulated anniling method

The algorithm starts working with the initial (background) impedance model mi . Then there is a perturbation of the model parameters mi , which can be changes in impedances and layer thicknesses that generate the mi+l model. Then the decision to accept this perturbation or reject it is accepted. If the target function J(m) does not increase during a parameter perturbation, the perturbation is always accepted. If the target function increases, the new mi+l model is also accepted, but with some probability:

$$P = \exp\left(-\frac{J_{(m+1)} - J_{(m)}}{T}\right) \tag{3}$$

where T-parameter, called temperature.

The higher T, the more likely it is to accept a "bad" disturbance resulting in an increase in the value of the target function.

The fact that at any temperature T more than O 'bad' perturbations can also be accepted means that it is possible to exit the local minimum point of the target function. It is this feature of the annulling process that ensures that the global minimum is reached.

Process: random perturbation, repeated for some time with unchanged T. Then the temperature drops and the process starts again. The algorithm stops when the set minimum target function is reached, or at low perturbation does not lead to a noticeable change in the model.

3.2 Classification of seismic inversion algorithms.

Inversion can be considered as a deterministic or stochastic task and can be performed using seismic data pre (a seismogram) or post-stack (sections, cubes) (Figure A.1).

3.2.1 Deterministic inversion

The task of inverse seismic data can be considered as deterministic or stochastic. The result of any deterministic inversion is the only model of elastic properties that satisfies seismic data and a priori constraints. This type of inversion has long been a production standard and is necessarily used in projects to predict reservoir properties. But deterministic methods do not allow probabilistic estimation of the ambiguity of the solution of the inverse problem, which may affect the interpretation results. To reduce geological risks, various methods of verification of the obtained results are used: cross-validation (using part of the wells as control), attraction of a priori geological information, etc. From this point of view, it is important to develop a methodology for combining the qualitative (attribute analysis, spectral decomposition, etc.) and quantitative (seismic inversion) interpretation of seismic data.

3.2.2 Stochastic (geostatistical) inversion

Another approach to the prediction of reservoir properties is associated with the use of geostatistical predicting methods, including stochastic inversion. The first examples of the use of geostatistics in the oil industry can be attributed to the 80s of the twentieth century. But geostatistics is starting to become a truly production technology only now. By stochastic geostatistics we mean a group of methods, the result of which is a lot of realization (simulations) of the properties of the object under study, in particular, the goal of the geostatistical inversion is to create many realizations of acoustic impedance due to seismic and borehole data. For stochastic inversion, a number of statistical parameters are selected and used that are not required for deterministic inversion, first of all, these are semivariograms: horizontal and vertical, which allow taking into account the spatial connection of elastic properties. The result of stochastic inversion is a multitude of realizations of high-resolution impedances. The main advantages of geostatistical methods include the ability to obtain results on the scale of well logging data, while calculating the probabilistic assessment of predictive properties. The geostatistical approach allows you to combine information of different scales (geology, seismic, well logging) in the form of a single 3D digital geological model.

Of special interest is the comparison of the results of geostatistical and deterministic inversion (Figure B.1, B.2) [10]. Comparison of sections of volume distribution of "lithotypes" shows that the forecast for deterministic inversion has an integral character, while the geostatistical inversion allows to distinguish separate permeable interlayers of reservoirs, in particular those belonging to the "gravelite" zone. According to the description of the core, in square 7, the "gravelite" pile has the smallest capacity (4-5 m) and the geostatistical inversion allowed its further distribution. According to the results of the deterministic inversion, the "gravelite" zone stands out confidently only in the vicinity of square 2, where it has the maximum power (15 m). Thus, with the use of geostatistical inversion can be constructed high-resolution volumetric model of distribution of collectors and identified promising "gravelite" zones.

With all the positive aspects of seismic inversion, the restored impedance depends on many geological parameters: layer thickness, lithology, porosity, effective pressure, such as pore fluid. Well-founded methods and algorithms for working with elastic properties will be crucial for quantitative seismic interpretation in specific geological conditions. In addition, the use of a priori geological information increases the reliability of the forecast and makes geological sense. The elastic properties obtained as a result of seismic inversion are used to evaluate and predict all kinds of properties, ranging from porosity of terrigenous reservoirs to geomechanical properties of bituminous clays and fractured carbonates.

3.2.3 Pre or post stack inversion

The inversion operation begins with a real seismic trace. Since the amplitude and shape of each oscillation in the seismic trace affect the result, it is very important to maintain the phase and amplitude of the signal at the processing steps up to this point. Inversions of different types begin with different types of traces. The greatest differences are the inversions before and after the stacking. Most seismic surveys produce images from the summed data. Stacking is a useful processing step if certain conditions are met: the speed in the medium above the reflecting horizon can only change gradually, and the average amplitude along the summed paths should be equal to the amplitude along the path for a normal beam.

In many cases, these conditions are satisfied, allowing the inversion of the summed data, i.e. after summation. But with a significant change in the amplitude depending on the distance, these conditions are not satisfied, and the inversion is carried out along non stacking trace , i.e. before stacking.

3.2.4 Acoustic Inversion (AI)

The term “acoustic inversion” refers to the procedure for determining the most important characteristic of a medium model — the dependence of the acoustic impedance {lp = pVp) on time from recording reflected waves at normal incidence [11].

The main advantage of acoustic inversion is its computational efficiency and simplicity, since it does not require any special preparation of seismic data - all the necessary procedures listed above have long been a standard part of any processing graph. The resulting sections or cube of acoustic rigidity are often quite informative both on a qualitative level, greatly facilitating the interpretation of lithological facies and stratigraphic boundaries, as well as quantitatively: acoustic impedance is widely used in predicting the distribution of porosity and gas saturation of productive reservoirs. However, there are also such geological problems when the information obtained by acoustic inversion is not enough: for example, if it is necessary to build a detailed lithological model of the layer, it is not always possible to unambiguously divide the section into the required lithotypes only in the P-impedance field. Among the acoustic inversion algorithms that have gained the greatest popularity to date, the so-called Constrained Sparse Spike Inversion (CSSI) and various implementations of neural network inversion, one of the most advanced of which is the “genetic” method. (Genetic inversion)

Recursive Inversion

Recursive inversion method (in the Russian literature PAL (pseudo-acoustic logging)) it is the earliest and one of the simplest ways to transform the wave field into acoustic impedance distributions.[12] The essence of the method is to calculate the relative values of the impedances using a recurrent formula.

Previously, deconvolution operation is applied to seismic traces to increase the resolution of the recording. It is theoretically possible to restore the absolute values of acoustic impedances by combining the obtained pseudo-acoustic curves and a low-frequency background model. The main problem of this type of inversion is the impedance distortion due to the smoothing effect of seismic signals and the accumulation of errors over time.

Despite the simplicity and high speed of calculations, the recursive inversion method is less in accuracy than most modern optimization methods of seismic inversion.

Inversion based on conversion operator

The essence of the methods of acoustic amplitude inversion, based on the conversion operator, is to find a transfer filter, which at convolution with the wave field allows you to move from amplitude values directly to the distribution of acoustic impedance.

Inversion based on operator – Coloured Inversion (CI)

Based on empirical researches [13], the authors found that the inversion process can be approximated by filtration with a simple operator. The phase of such an operator should be constant -90 °, which corresponds to the idea of the transformation of zero-phase reflection into a jump (step) of acoustic impedance. WaJden and Hosken showed that the spectrum of reflection coefficients can be represented by the trend f ^ β, where β is a constant, f-frequency. The same behavior is observed for the acoustic impedance spectrum, but the exponent is negative. The amplitude spectrum of the inversion operator is obtained by combining the amplitude seismic spectrum and the acoustic impedance spectrum in the wells. Further, the obtained operator is applied to seismic data.

Color inversion is a simple and fast way to invert data and can be applied at the initial stage of dynamic interpretation. The algorithm allows you to get a more accurate result than a recursive inversion, but inferior to more advanced optimization methods of inversion.

Genetic Inversion (GI)

The method of genetic inversion or GI proposed by I.I. Priezhev refers to the type of acoustic seismic inversion based on the operator. The algorithm consists in converting seismic data into a filtration-capacitance distribution (FCD) using a nonlinear operator. This method assumes the use of only one seismic cube with initial amplitudes at the input of neural networks. Seismic observations are fed to the input in a certain sliding area around a central point, which corresponds to the observation at the well during training [14].

The algorithm can be conventionally attributed to detrmenistic inversion, based on the principle of neural network training on acoustic data on wells and seismic cube. According to the found dependence, the acoustic property cube is calculated, which was used for network training (it can be both an impedance and another property that has a connection with the acoustic characteristics of rocks).

For the first time, the method of using neural networks for building a property cube based on seismic data is described in D. P. Hampson and others, where a set of seismic attributes was used at the neural network input. This method is implemented in many systems, including Petrel, and has been widely tested. The complexity of this approach is that it is very difficult to define a set of working seismic attributes, which should be special for each project. In addition, there is no possibility to manage forecast quality using this approach, and there is a risk of overtraining neural networks.

The algorithm of genetic inversion has been tested on real data for studying collector properties in mixed terrigenous carbonate thickness.

For comparison, the inversion was performed in two ways (Figure B.3):

-deterministic inversion based on convolution of the convolution operator in the spectral region with a given impulse. For the inversion, a standard rocker-pulse with a maximum of spectrum was used

at 30 Hz (figure B.3, b);

-genetic inversion. Training of the neural network was carried out for one well on the basis of acoustic impedance data obtained from acoustic logging and density data; four wells were used to verify the quality of training (see Figure B.3, c).

By comparing the results of deterministic and genetic inversions, we can draw a conclusion about their identity as a whole. The results of genetic inversion show better comparability with well data. This proves the reliability of the proposed algorithm results.

Sparse Spike Inversion (SSI)

The main idea of Sparse Spike inversion is to restore the impedance model that corresponds to the seismic frequency band, and then combine the resulting solution with the background, low-frequency model, thereby reducing the ambiguity of the final solution. The family of algorithms for rare pulse inversion or SSI is based on the Oldenburg et al. criterion, which allows selecting one of the many inversion solutions that corresponds to the physical problem statement. This criterion is to ensure a minimum sum of modules of the desired reflection coefficients in the seismic frequency band.

Due to the high accuracy and stability of the resulting solution, the SSI method is one of the most common, widely used seismic inversion algorithms used in production and having the largest number of modifications. The main types of SSI are Constrained Sparse Spike Inversion.

Constrained Sparse Spike Inversion (CSSI)

By using optimization methods for find a solution, the algorithm for the Constrained Sparse Spike Inversion or CSSI is the most technologically advanced modification of SSI, which allows to obtain accurate results. Based on the name, the main idea of the CSSI method is to add additional constrains to the objective function.

CSSI inversion converts the seismic data into a pseudo-acoustic impedance curve in each trace. Acoustic impedance is used to obtain a more accurate and detailed structural and stratigraphic interpretation compared to seismic interpretation (or interpretation of seismic attributes). Many geological settings are characterized by the presence of a stable connection of acoustic impedance with petrophysical properties, such as porosity, lithology and fluid saturation.

A “good” CSSI inversion algorithm allows you to obtain four high-quality cubes from the total seismic data: the impedance cube in the full frequency range, the impedance cube in the limited frequency band, the reflection coefficient model and the low-frequency component. Each component can be examined for relevance for the choice of a solution, as well as for quality control of the results.

Due to the mathematical complexity of the parametric functional and the introduction of additional restrictions, the CSSI algorithm allows you to take into account more a priori information, which in turn leads to an increase in the accuracy of the final solution.

Model Based Inversion (MBI)

One of the most popular and commercially successful methods of acoustic inversion is a model-based inversion method.(MBI)

The essence of the model-based inversion method is to find the optimal solution based on the initial approximation. Within the limits of the set restrictions, the a priori model is corrected at each iterative step until the optimal model of elastic properties is found. The most famous MBI algorithm uses the low-frequency approximation as the initial model. The idea of this approach is based on a convolutional model of a seismic trace. The reflection coefficients at normal incidence (ri) are determined by the values of acoustic impedances (AI).

Generalized Linear Inversion (GLI)

The process of inversion is called generalized linear inversion because it starts with some primary approximation of the solution, followed by consecutive clarification of the solution by means of a number of small steps. Each step improves the correspondence between synthetic and real data. The GLI method is based on decomposition of the function into Taylor series.

The generalized linear inversion or GLI algorithm proposed by Cooke D.A. and Schneider W.A. has been developed as an alternative to the recursive inversion method, which solves the problem of estimating the absolute values of acoustic impedance and the sensitivity of the resulting solution to seismic noise while maintaining the simplicity and high speed of calculations. The GLI method allows describing continuous properties of the real environment by block or layer curves, which are associated with lithology.

To stabilize the solution, the GLI algorithm uses a rigid assignment of a priori information about the properties of the studied section, which consists in fixing the values of acoustic impedance in individual reference layers. Thus, the optimal solution of the GLI algorithm is a model that is as close as possible to the a priori distribution and forms a minimum disturbance between synthetic and measured wave fields.

Inversion based on a low-frequency model (LF MBI)

In the most known model based inversion algorithm, a low-frequency approximation (LF MBI) is used as an initial model. The idea of such an approach is based on a convolution model of the seismic trace. As an initial approximation, an acoustic impedance low-frequency model built by interpolating well data on a stratigraphic grid and filtered to the lower boundary frequency of seismic data is used.

Like the CSSI algorithm, the LF MBI method is one of the most common tools for dynamic interpretation of seismic data.

Layered Amplitude Inversion

The method of layered amplitude inversion is one of the representatives of the class of algorithms of deterministic seismic inversion based on the model. The main feature of the method is that it takes into account multiscale geological and geophysical data in the search for an optimal solution, as well as presentation of the result in the form of formation curves. This approach allows to estimate the distribution of elastic properties within each layer, as well as to obtain information about the position of the roof and the bottom of each layer in the time domain.

The method is based on an idea proposed by Cooke D.A. and Schneider W.A., which was further developed in the works of I.K. Kondratyev.

Conditionally, the work of theLAI algorithm can be divided into three stages. The first stage includes creation of one-dimensional reservoir models of elastic properties on the basis of well data on the basis of analysis of properties of the studied section at different scales, passing from smaller to larger: core → well logging → seismic exploration. As a result, formation models combining thin layers with close petroelastic properties are calculated.

The second stage consists in building an a priori formation model, which is used as an initial approximation by interpolating one-dimensional downhole formation models using a grid structural framework. The size of each grid cell is irregular and depends on the time value of each formation and the size of the bin (in case of 3D survey) or the distance between seismic traces (in case of 2D survey).

At the final stage, the search for an optimal solution in the form of formation curves is carried out using optimization methods, taking into account the "reference" layers, for which tighter limits of elastic properties and thicknesses change are set.

3.2.5 Elastic inversion

The amplitudes of seismic data at normal incidence (at close distances) are associated with changes in acoustic impedance, so seismic data can be linked to borehole data using a synthetic trace calculated from an acoustic impedance curve. In 1999, R. Connolly introduced the concept of elastic impedance as a generalization of acoustic impedance for non-zero incidence angles. Elastic impedance is the basis for referencing seismic data as well as its inversion at long distances.

The elastic inversion or pre-stack inversion is a set of methods for estimating elastic properties (Vp,, and their derivatives) from pre-stack seismic data. In contrast to acoustic inversion, the distribution of reflection coefficients in the elastic inversion is a function of longitudinal (Vp) and transverse wave velocities (Vs), density (ρ), and angle of incidence, which can be obtained from seismic data using the Zoeppritz equation system or linearized approximation of Aki and Richards. Elastic inversion can be done in 2 ways:

1. Direct methods of inversion based on the operator, using which parameters of layers are consistently recalculated from layer to layer.
2. Methods based on a model. They consist in the fact that, having modern computational tools, it is possible to synthesize a large number of seismic models for different combinations of elastic parameters and select from the models the one that best matches the real data. The elastic parameters included in this model will be the result of inversion. The purpose of elastic inversion is to obtain an adequate real model of the medium at a minimum of iterations (organization of data processing, in which the actions are repeated many times without resulting in self-inflicted challenges).

Extended Elastic Inversion (EEI)

The Extended or Continued Elastic Inversion (EEI) methodology proposed by Whitcombe D.N. and others is a continuation of the development of ESI technology for dynamic interpretation of seismic data.

The main advantage of the EEI algorithm is the transformation of the amplitudes of the wave field into a set of curves (χ), which at a certain value of the angle (χ) have a high correlation coefficient with various physical parameters, such as acoustic impedance, volume module, Lame constants, etc. In some cases, as the sought parameters are inelastic properties (gamma-activity, water saturation, sandiness coefficient, etc.), which also have a high correlation coefficient with EEI (χ) at appropriate angles (χ).

Thus, the EEI method is a universal tool that allows seismic data to obtain distributions of elastic and lithological properties in case of a stable correlation between the values of (χ) and the required parameter.

3.2.6 Simultaneous (synchronous) inversion

The purpose of simultaneous inversion or inversion of pre-stack gathers is to reconstruct the model of P-wave velocities (Vp) of transverse waves (Vs) and density (p). This inversion method is the most advanced one, as it allows extracting the maximum information required for qualitative and quantitative interpretation of data from seismic data. On the other hand, synchronous inversion is more demanding to the quality and quantity of input data.

The advantages of the simultaneous inversion method. The simultaneous inversion algorithm evaluates the impulses for each angular sum individually. Thus, all variations in amplitude, frequency and phase composition of different data cubes are taken into account and there is no need for scaling, frequency balancing and phase correction. The program finds the best model of the environment using an algorithm of amplitude alignment, uses continuous trace comparison to reduce noise, variable pulse horizontally and vertically, the ability to change the low-frequency component through primary models, and has the ability to work with very large volumes of data without segmentation. ISIS is able to work with different sets of seismic data: standard angular sums (PP AVO), exchange cross-wave cubes at bottom recording (PS AVO), cubes and 4D seismic angular sums. Simultaneous inversion into ISIS is performed directly on the required physical parameters, without additional processing procedures.

— For AVO data it can be acoustic impedance (AI), Poisson's coefficient (δ) and density (ρ) or acoustic impedance (AI), elastic impedance (PI) and density (ρ).

— For exchange cross-wave cubes it is an elastic impedance and density. For 4D seismic cubes, the primary acoustic impedance and its residual values between all subsequent surveys are calculated simultaneously.

— The 4D AVO inversion calculates the physical parameters for the primary survey (AI, δ, ρ) and their changes from survey to survey. The distorting effect of reflection interference and impulse shape changes on the results is eliminated, thus building a thin layered model of the geological medium. As a result, the inversion produces physically informative values of petro-acoustic parameters of rocks - values of velocities of propagation of longitudinal waves (Vp) and transverse waves (Vs) [15].

4 Examples of seismic inversion calculation.

4.1 Acoustic inversion

When we are calculate acoustic inversion, the main components are seismic impedance (acoustic stiffness), determined from well logging data, and pseudo-porosity (porosity calculated from seismic data). Seismic data have a limited bandwidth, which in some cases decreases the resolution of seismic exploration and reduces the quality. In order to extend the existing frequency range, log data are used to obtain a low-frequency component. Well logging data are used to add a low-frequency component outside the seismic bandwidth and thus introduce limits to the inversion result.

Input data and task definition. The main input data for the logging when calculating inversions are measurements of acoustic and density methods. For our example, the volume of these data was quite extensive: density logging (D-GGL) was performed in 581 wells, and acoustic logging was performed in 584 wells. In 19 wells VSP was carried out. The conditions for obtaining a qualitative result of amplitude inversion are uniform distribution of wells over the area, as well as such a number of wells as is sufficient to describe the sedimentation model. Therefore, 30 wells were used from an extensive well stock.

For practical realization of inversion transformations it is necessary also data of a seismic cube of time migration before stacking; structural maps on surfaces of geological interest, and also stripping of these horizons on the above mentioned wells.

In the studied section, the collectors of terrigenous Lower Cretaceous and Middle Jurassic sediments are represented by weakly cemented sandstones (sands) and siltstones (silts) with an insignificant content of clay material. The effective reservoir thicknesses of the productive strata range from 0.3-12.1 m for Neocomian rocks and from 0.3-28.4 m for Middle-Jurassic rocks. Thus, an amplitude inversion of seismic data was performed on the combined seismic cube in the study area in order to study in detail the structure of the Neocomian and Middle Jurassic productive intervals and determine the nature of saturation of sandstone layers.

Analysis of petrophysical characteristics

For tasks of dynamic interpretation it is important to study the stiffness characteristics of the studied thicknesses, which in the logging complex are represented by density and acoustic methods.

Before the beginning of the analysis of petrophysical properties the field and geophysical curves were prepared in a special way: the independent logging material was connected, in a number of wells an additive correction was made to DT (acoustics) and RHOB (density) curves. In addition, the RHOB, DT curves were smoothed in 0.5 m vertical increments and the high-amplitude emission intervals were corrected. As a result, material suitable for the analysis of petrophysical properties of the section was obtained.

At the first stage, it was established which of the rigid parameters best solves the problem of dividing the section into collector / non-collector. Histograms of distribution by speed DT, RHOB density and acoustic impedance AI values were constructed for this purpose (Figure C.1).

As you can see from Figure C.1 (a), value of the acoustic logging curve for reservoirs (green) and non-reservoir are almost the same. Thus, it is practically impossible to divide rocks into reservirs/non- reservoirs by speed values. Density distribution (Fig. C.1 (b)), on the contrary, shows a rather confident division of rocks, the probability of which is significant and is ~ 70%. Then we analyzed the possibility of rocks separation by acoustic impedance values. A histogram of acoustic impedance distribution of AI is presented in Fig. C.1 (c). From the histogram we can see that the division of rocks into reservoirs /non- reservoirs by acoustic impedance is difficult, the separation is not strongly pronounced and does not allow to reliably estimate the share of collectors by AI values, but there is a trend of increasing AI values for some reservoirs.

A series of cross-splots (Figure C.2) of the species P-wave porosity/velocity, porosity/volume density, porosity/acoustic impedance was constructed to evaluate the tightness of the relationship between the stiffness parameters of the medium and porosity. In their construction, the influence of clayiness on the determined porosity values was analyzed.

The analysis of dependencies showed that there is a rather close relationship only between volumetric density and porosity (Figure C.2 (b)). Comparison of Vp=f(Cp) shows the missing relation between the parameters of Figure C.2 (a, c), so the change of porosity of the rock practically does not affect the values of velocity.

So, for productive deposits of the study area, the density is an informative parameter, which allows to estimate both the quality of the reservoir and to distinguish the intervals of reservoirs in the thickness.

So, it is expedient to calculate the density cube to observe the lithophacic zones. However, in the available mathematical support, the background model should be either in the values of acoustic stiffness or in the values of speed. For this reason, the downhole density curves have been recalculated by the Gardner equation into a velocity curve (further in the text - pseudo-speed). Since the seismic response is generated at the boundary of the impedance change (the result of multiplying velocity and density) rather than density, it is necessary to obtain an impedance cube to control the validity of the area distribution properties. Thus, two amplitude inversions from the same seismic data but with different background models and individual tuning parameters are performed.

Calibration of borehole and seismic data

Calibration is performed to calculate the impulse shape best suited for linking synthetic seismic traces calculated from log curves to real seismic traces obtained after processing.

Calibration consisted of several steps:

- Multi-channel analysis of the impulse shape is the calculation of zero phase impulse on given parameters of the amplitude-frequency spectrum on a group of traces of the seismic cube.
- Selecting the working time interval for calibration
- Determination of time shifts between synthetic and real traces
- Determination of phase shifts between synthetic and real traces
- Normalization of synthetic trace energy
- Refinement of the effective impulse - oversampling phase and amplitude corrections.

The accurate evaluation of the impulse is very important for the success of any inversion, and the predicted shape of the seismic impulse may affect not only the result of the seismic inversion, but also the further evaluation of the filtration capacitive properties of the productive zones.

If the evaluated (constant) phase of the statistical impulse is coordinated with the final result, then the process of evaluating the impulse converges faster than in the case of the assumption about the "zero phase". Insignificant editing and procedure "stretching and compression" can be used for the best combination of axes of sinphasicity. Accurate impulse estimation requires accurate coupling of the impedance curve to seismic data. Errors made when referencing wells can lead to phase or frequency distortions in the pulse estimation.

When the impulse is determined, a synthetic curve is calculated for each seismic trace. To ensure better quality, the inversion result is minimized to a pulse to produce synthetic seismic traces that are compared to the original seismic. Without a seismic impulse, the solution will not be unique.

Evaluation of the seismic data spectrum in the time window >300 ms has sh own that the frequency range of the recording is 12-150 Hz (Figure D.1).

The signal extracted from real seismic data has almost zero phase characteristics. When comparing seismic and synthetic traces, it was possible to determine the pulse shape in which the values of the cross-correlation are maximum. A synthetic trapezoidal impulse with a working frequency range of 12-65-85-150 Hz was selected. Synthetic seismograms were obtained by convolution of the pulse with the trace of reflection coefficients calculated from the block curves: in one case - pseudo-speed (density function), in another - acoustic impedance. Thus, synthetic seismic trace were calculated for 73 wells and linked with seismic data. It should be noted that there is a good convergence of well and seismic data for both impedance and pseudo velocity (Figure D.2).

Based on the results of well tying 33 wells were selected, which participated in the construction of the background model. The background model is used both as a constraint in the solution optimization process and as a low-frequency component to restore the full environmental characteristic. The main results of the background model use are detailed models of impedance (Figure D.4) and pseudo velocity.

Seismic inversion

Inversion of seismic data was conducted in a constant time range of 110-890 ms. The total (5-30° angle range) time cube with the corresponding signal and recalculation factor as well as cubes of filtered background models were fed to the inversion input: in one case of impedance, in the other - pseudo-speed. Thus, the impedance and pseudo-speed cubes were obtained.

Based on the possibility of lithological dissection of the section by the pseudo-speed parameter, histograms of the distribution of the parameter by individual lithophases were calculated and the vertical pseudo-speed section was compared with the gamma logging curve and the interval collector curve. Based on the results of this stage, pseudo-speed values were selected for three main lithotypes (Table E.1)

In the value of pseudo-speed, each lithotype was given a corresponding number (third column). For a clearer breakdown of the rocks for the Triassic sediments was given a number 40.

Thus cubes of porosity (Figure E.1) and lithology (Figure E.2) were constructed [17].

4.2 Elastic Inversion

Create a project and upload data to the Interwell software package.

The project was created inside the Interwell software package and the following data were loaded into it: seismic cube of prestack time migration, time scale logging curves for wells A, B and C, seismic horizons J-XIII (roofing J1), V(roofing T3) and V2 (roofing T2), as well as stripping of these horizons from the above wells.

The time interval in the zone of interest (1500-3000 ms) corresponding to the Jurassic and Triassic stratigraphic complexes was chosen for inversion.

Calibration of borehole and seismic data

During calibration procedure the working frequency range (Figure F.1) equal to 14-26-70-90 Hz was selected. This choice was due to the presence of residual interference from surface waves (12-17 Hz) and good amplitude characteristics of useful reflections in the target time range at frequencies up to 80-85 Hz.

As a result of calibration, good correlation results were obtained between synthetic and real traces. An example of such calibration is shown in Figure F.2 for well C (synthetic traces in the center and real traces on the right and left).

Construction of an impedance model

The impedance modeling procedure generates a multi-parameter geophysical model, which should correspond to a geological sedimentation model. The model built is then passed to the inversion input.

This model of density properties and seismic impedances includes logging curves, interpreted seismic horizons, and selected sedimentary models within each geological group.

The corresponding set of seismic horizons is loaded into the structural modeling module to build a time scale structural plan, which will play the role of an a priori geological model. Within each geological group of deposits, correlated surfaces are generated from the interpreted sedimentary models. These surfaces are further used as reference surfaces for interpolation and extrapolation of the structural model from the existing reference points of the well location. The fragments of the model built are shown in Figures G.1 and G.2.

Seismic inversion

The elastic inversion solution method consists in a multi-channel approach based on the construction of a regular grid (grid) taking into account a priori information along correlation surfaces specified in the initial model. In the course of optimization, the solutions took into account the interpreted structural plan and stratigraphic elements. In other words, geological information was used to set limits for inversion, i.e. to exclude the known problem of numerous possible inversion solutions.

Results of the inversion

The result of the inversion was a cube of impedances and a cube of pseudo-porosity (porosity calculated from the cube of seismic impedances).

Figures G.3, G.4 and H.1 show the inversion results in the zone of interest (Lower Jurassic and Upper Triassic). On the maps we can see denser and more high-speed rocks (darker zones) and decompaction zones (red areas).

The pseudo-porosity sections (Figure H.2) also show sharp porosity boundaries by stratification of the target interval (blue boundaries are small porosity, red boundaries are large).

Impedance maps between the Lower Jura and Upper Triassic horizons were also analysed. Figure H.3 shows the distribution of impedances between reflecting horizons J-XIII and V.

From these data we can see that wells A_4 and A entered the zone of dense and high-speed rocks. Impedance and pseudo-porosity cuts also show that there are very dense rocks with low porosity in the bottomhole area of well A, which could have been the reason for the accident (tool sticking).

In addition, data from the coherence cube were analysed. The coherence cube is an additional three-dimensional attribute that provides good coverage of the spread of the crack and fracture network over the study area. From the data of the coherence cube and the faults, which were identified from seismic data, we can see that wells A_4 and A fall into the zone of blockages and faults. Well A_4, in particular, is located directly on the fault (Figure H.4).

4.3 AVO- inversion

Another example of dynamic interpretation of a joint cube of seismic data is the AVO-inversion, which is performed for the purpose of detailed study of the structure of productive intervals.

The AVO-analysis technique involves studying the amplitudes of reflected waves depending on the angle of incidence of the waves on the reflecting boundary. Thus, the amplitudes of not only longitudinal waves, but also those arising on remote channels of exchange reflected waves, which react to the presence of fluid (especially gas and oil) in porous media differently than longitudinal waves, which causes the appearance of AVO-anomalies (bright spot effect). Note that amplitude anomalies may be associated not only with fluid saturation, but also with changes in lithology, power, and elastic properties of the formations composing the geological section. Thus, AVO-analysis helps to identify more reliably the areas with improved reservoir properties, as well as areas of proposed HC saturation.

First of all, AVO attributes are calculated. For this purpose, a cube of seismograms is used after a temporary pre-stack migration with corrected residual kinematics.

To improve the quality of input gathers, band-pass filtration (0-20-140-160Hz) and median filtration (15%) have been performed, providing for the increase of S/N ratio. In addition, seismograms were limited to internal and external muting (5°-50°). Seismograms were grouped in superseismograms with the base equal to 3 CDP. Additional iteration of residual kinematics correction was performed to obtain optimal result. To obtain zero phase sections, phase rotation by -70° was applied, which was established as a result of linking seismic and well data.

By comparison of initial gathers and gathers after preliminary processing it is visible that quality of the latter has improved and S/N ratio has increased (Figure I.1).

Partial angular sums were also calculated for different ranges of incidence angles: near angles varied between 5°-15° (Near Angle Stack), medium angles varied between 15°-25° (Medium Angle Stack), far angles varied between 25°-35° (Far Angle Stack) and partial angular sums varied between angles 5°-30° and 5°-50°.

A qualitative analysis of the calculated partial angular sum cubes and AVO attributes was then performed. The conducted analysis is presented on the examples of the 5°-30° angular sum cube and the AVO attribute of Fluid Factor - deviation from the background line (Mudrock Line) corresponding to water-saturated rocks, which displays the HC saturation of incision intervals.

Figure I.2 a shows a section of a partial angular sum of 5°-30° and a map of minimum amplitude values for this cube taken along the NeoA1 horizon.

It can be seen that in the neocoma interval and above the seismic section is strongly complicated by the background of migratory noise, which is reflected in the amplitude map. To improve the quality of seismic data, a procedure to subtract migratory noise has been carried out, which has significantly improved the traceability of reflecting horizons (Figure I.2 (b)) and has resulted in a more stable area distribution of amplitudes without distorting the dynamic characteristics of the seismic field.

An example of the calculation of the Fluid Factor AVO attribute is shown in Figure J.1

Cube of partial angular sum in the range of 5 °-50 °, was recommended for attribute analysis, because in the target Neocomian deposits, it gives the most complete information about the lithological heterogeneity of the section and is characterized by higher resolution, which increases the informative value of the inversion.

According to the drilling data, gas-saturated intervals are distinguished in the structure's vault. It is known that the presence of this fluid significantly worsens the quality of seismic data, which is expressed in the change of frequency characteristics and distortion of amplitudes. Figure J.2 shows an example of a seismic section at an angular sum of 5°-30° with characteristics of the frequency spectrum inside and outside the gas influence zone. It can be seen that within the zone lower frequencies prevail in seismic data and there are no higher frequencies. Frequency spectrum analysis showed changes up to 20-25 Hz.

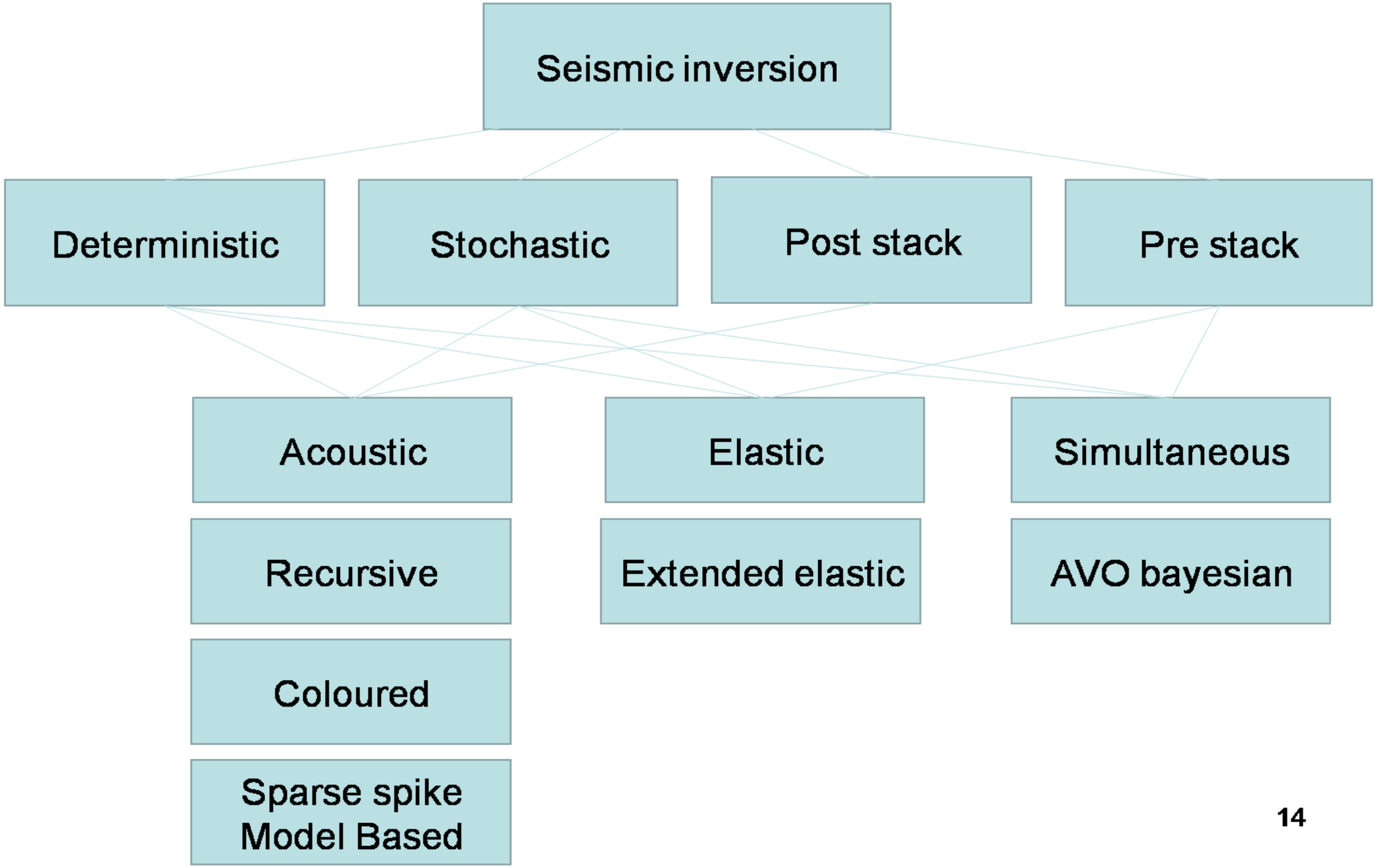
The presence of gas in the section also affects the dynamic characteristics of the section. Figure J.3 shows amplitude and coherence maps taken along the A2_up horizon. On the amplitude map, the zone is expressed by a sharp fading of amplitudes. In terms of coherence, a saturation contour is clearly outlined.

Coherence (similarity) - is a wave attribute that describes the rupture of solidity of rocks and local layering disorders such as faults, drops, thrust, etc. If a formation breaks and shifts, or a fracture without shifting, or there is a change in acoustic stiffness in the formation without changing the geometry, the coherence decreases. Thus, the coherence cube calculation is an integral part of the structural interpretation process and helps to identify a disturbance in the coherent seismic signal recording in fracture, tectonic dislocation, flexural and lithological substitution zones.

CONCLUSION

Intensive development of the dynamic interpretation direction in seismic exploration has led to the appearance of various algorithms of seismic inversion, differing in mathematical approaches and accuracy of the solution of the geological problems, but united by one goal - to obtain a reliable distribution of elastic properties in the studied layered medium.

The benefits of seismic inversion that solves a wide range of problems in forecasting volume distribution of various petrophysical parameters of productive layers are highlighted. By the example of seismic and well logging data the informativity of seismic inversion in search of oil and gas objects and determination of their filtration-volume properties has been studied. For all types of inversion, the following are crucial: the ability to flexibly account for a priori information by defining search boundaries. Required values of elastic properties, as well as optimization of formation boundaries position in space. The choice of inversion method depends on the initial data and task allocation in a survey area.



Seismic inversion

Deterministic

Stochastic

Post stack

Pre stack

Acoustic

Recursive

Coloured

Sparse spike
Model Based

Elastic

Extended elastic

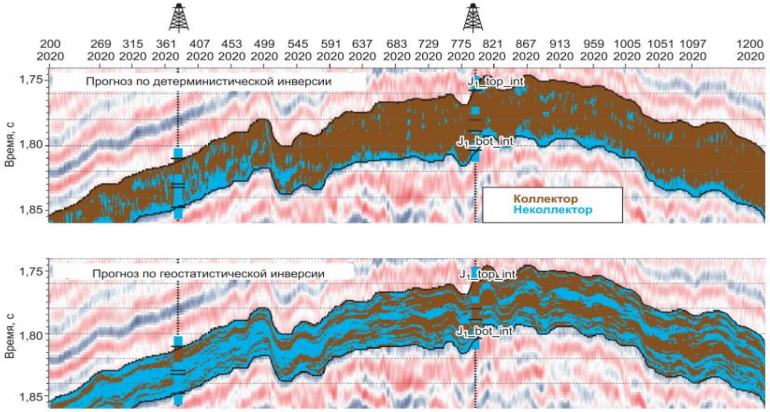
Simultaneous

AVO bayesian

Attachment A

Figure A.1 - Classification of seismic inversion algorithms

Attachment B



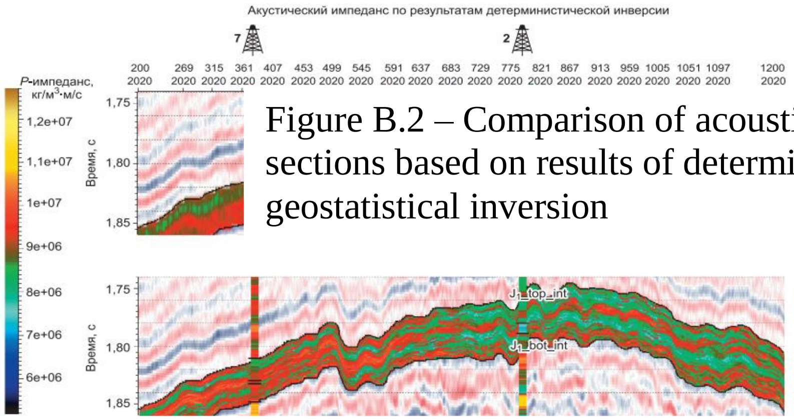
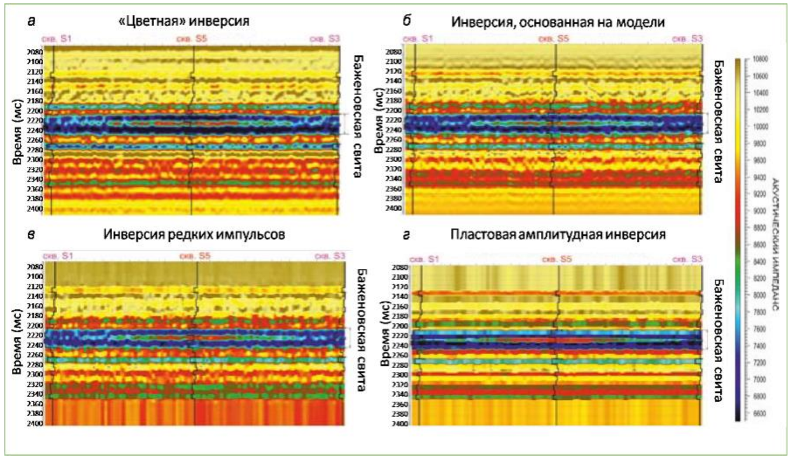


Figure B.2 – Comparison of acoustic impedance sections based on results of deterministic and geostatistical inversion

Figure B.1 – Comparison predicted sections based o deterministic and geostati

Figure B.2 - Comparison of acoustic impedance sections based on results of deterministic and geostatistical invrsion



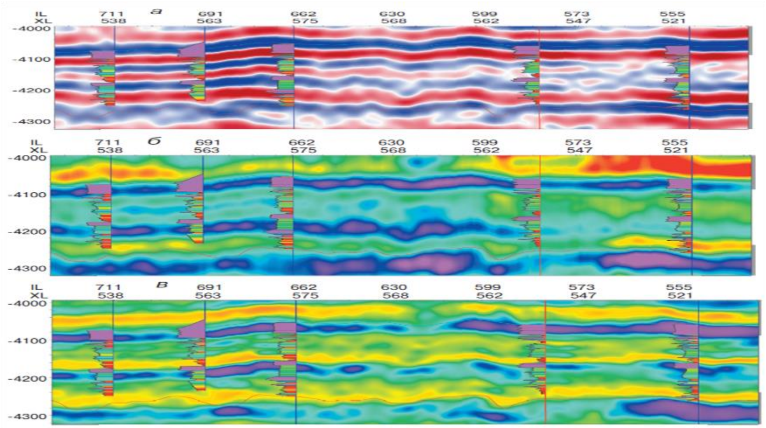
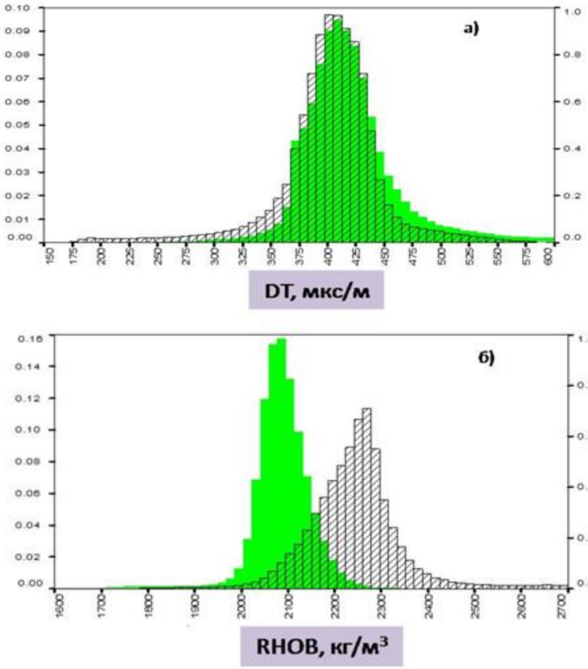
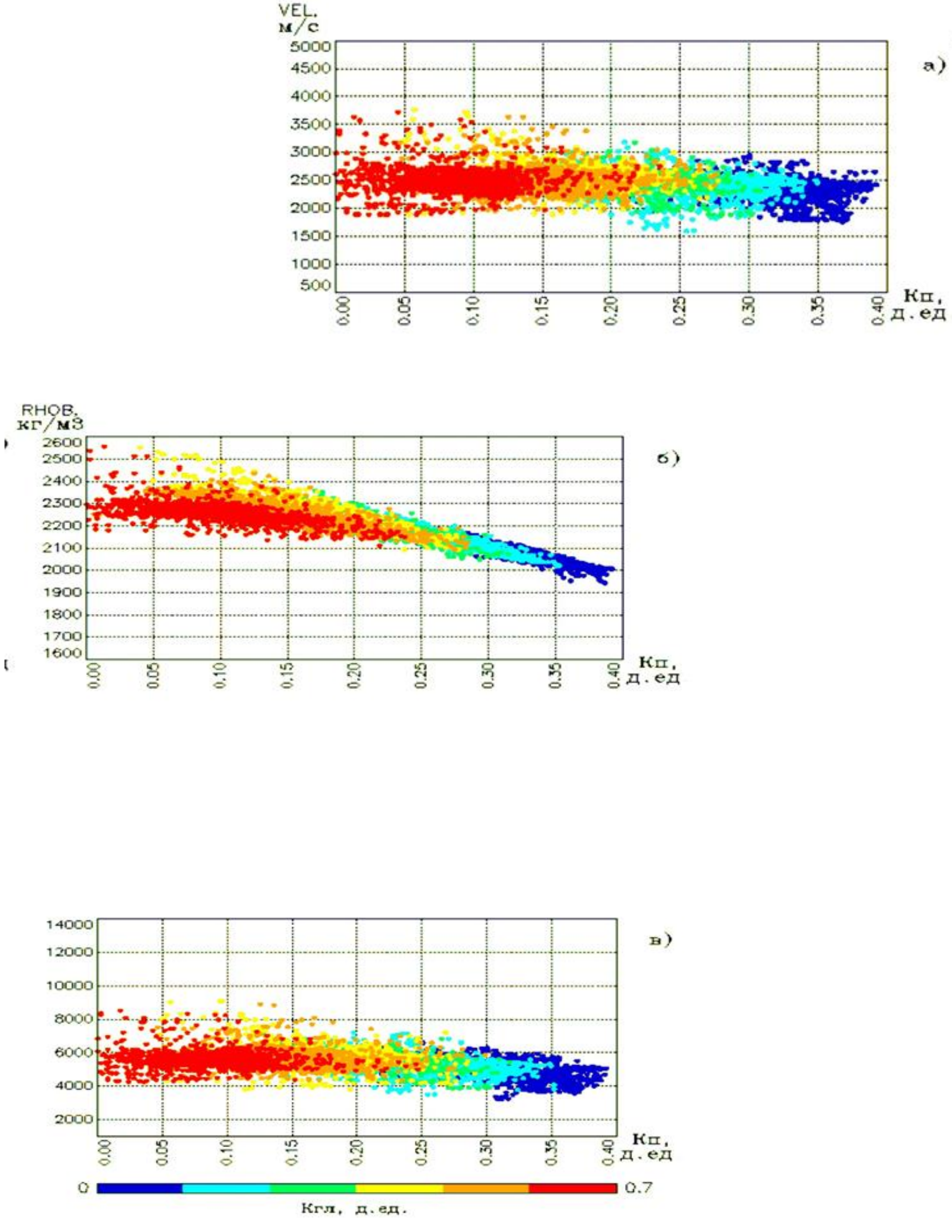


Figure B.3 - The result of acoustic seismic inversion of model data with using algorithms



Attachment C

Figure B.4 - Comparison of results of deterministic and genetic inversion



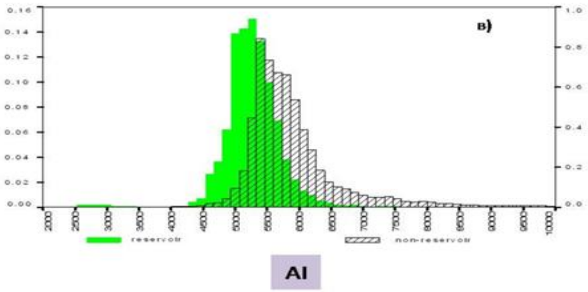


Figure C.1 - Distribution histograms of reservoir-non reservoir DT, RHOB, AI by well data

Figure C.2 - Estimates of the relationship between stiffness parameters of the medium and porosity

Attachment D

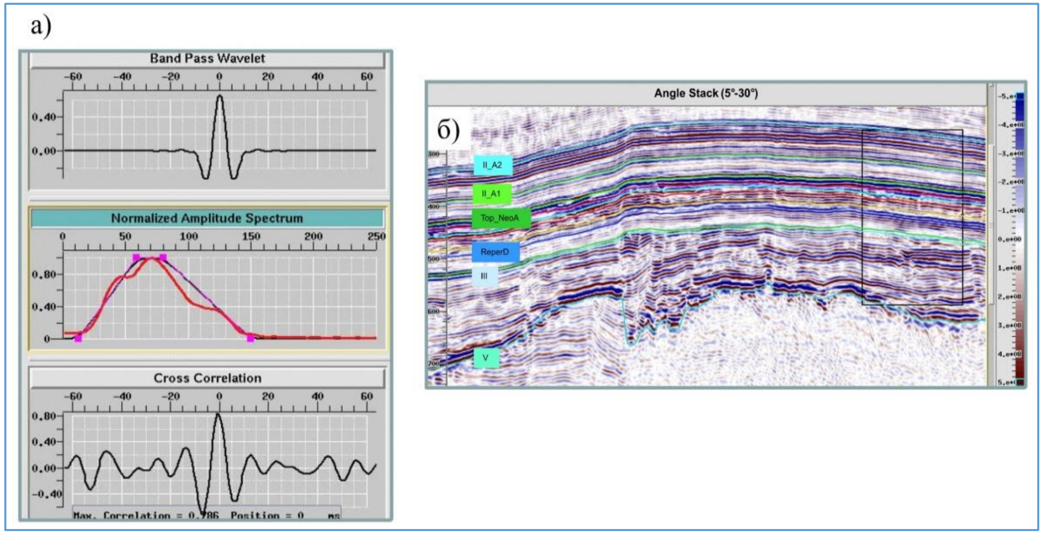
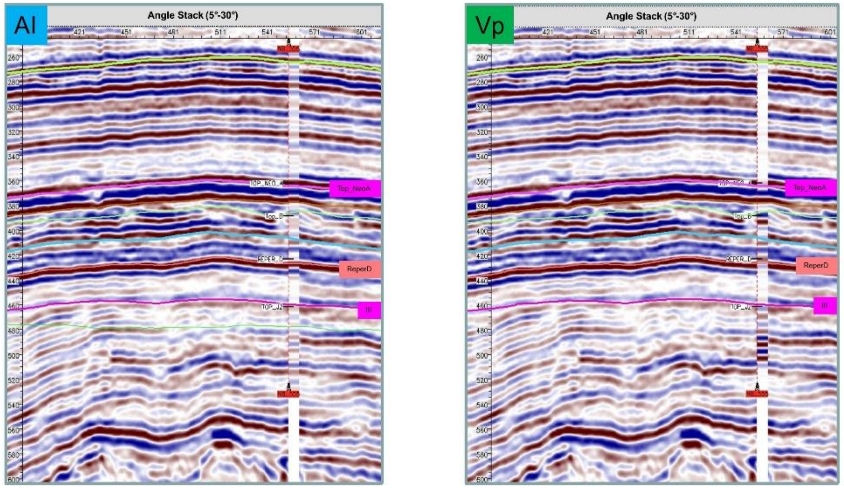


Figure D.1 – Frequency-phase characteristics of the signal (a), time interval selected for signal evaluation (b)



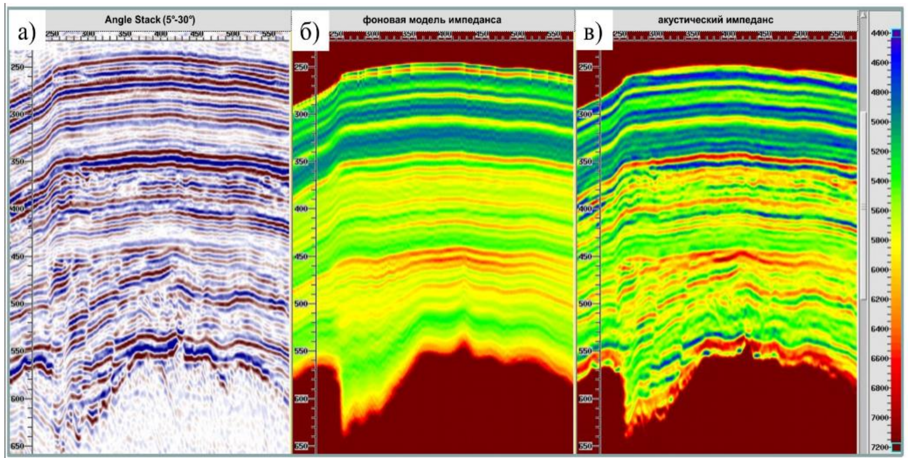


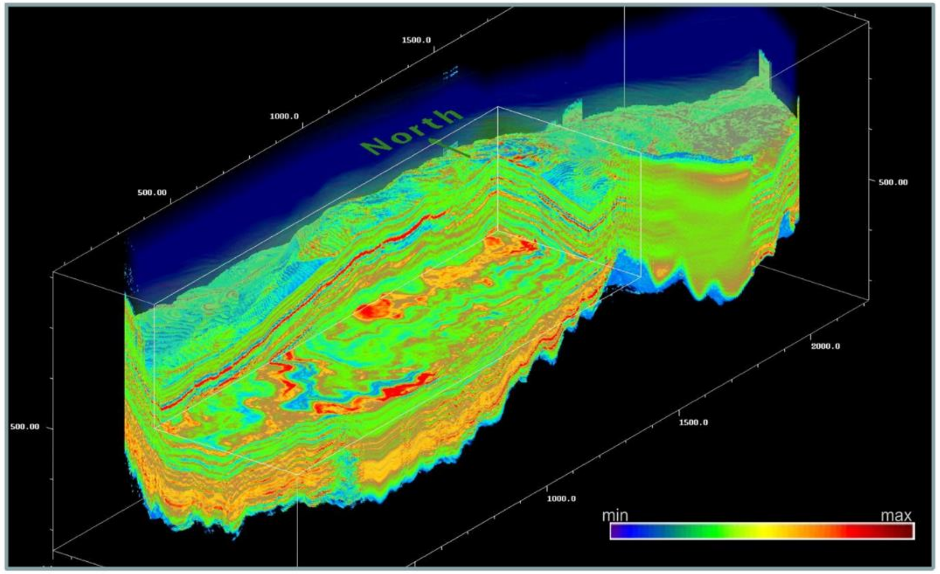
Figure D.2 - Result of well and seismic data calibration

Figure D.3 – Example of inversion result based on seismic data section (a) and background impedance model (b)

Attachment E.

Sandstone	Vp<3350	10
Siltstones	3350<Vp<3550	20
Clay and dense rocks	Vp>3550	30

Table E.1 – Values of pseudo-speed for the three main lithotypes



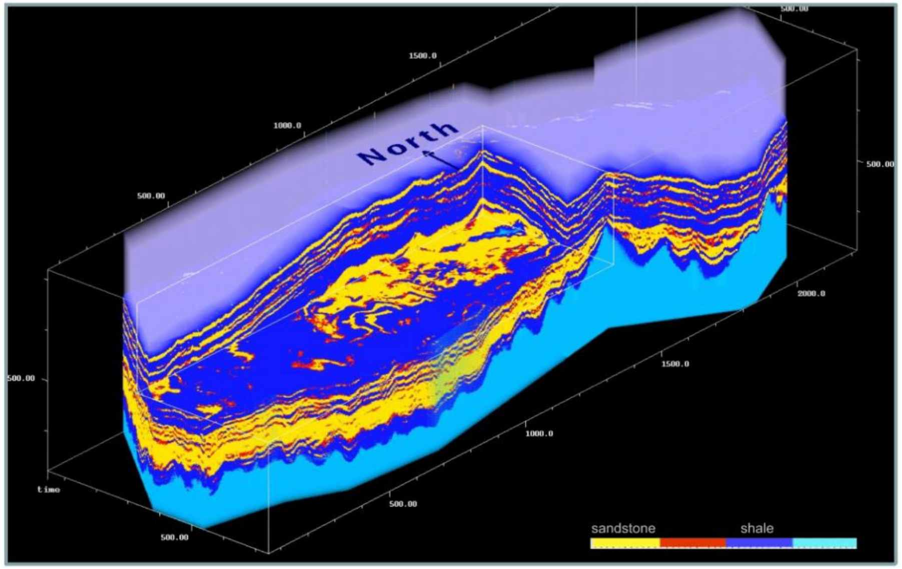
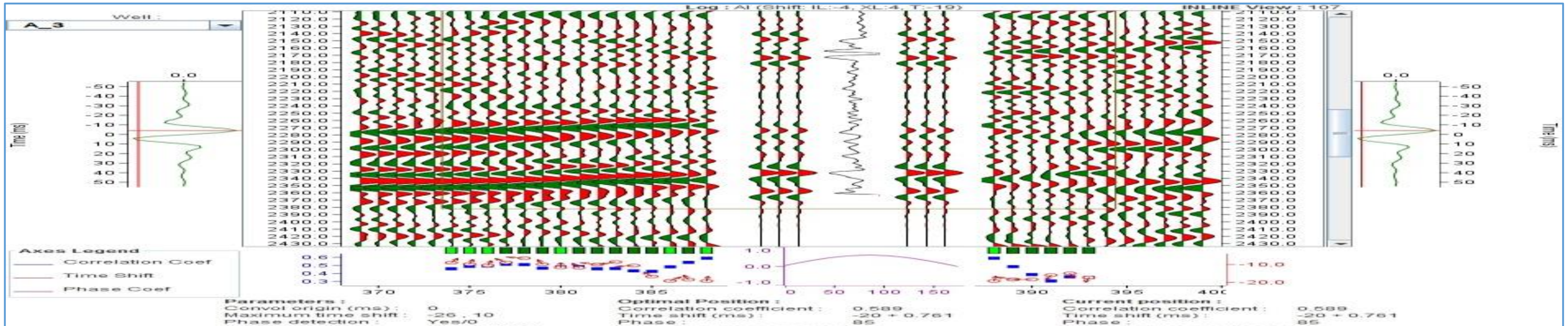


Figure E.1 – Cube of Porosity

Figure E.2 - Cube of Lithology

Figure F.1 - Amplitude spectrum analysis

Attachment G



Parameters :
Convol origin (ms) : 0
Maximum time shift : -26 , 10
Phase detection : Yes/0

Optimal Position :
Correlation coefficient : 0.589
Time shift (ms) : -20 + 0.761
Phase : 85

Current position :
Correlation coefficient : 0.589
Time shift (ms) : -20 + 0.761
Phase : 85

Figure F.2 - The result of borehole and seismic data calibration

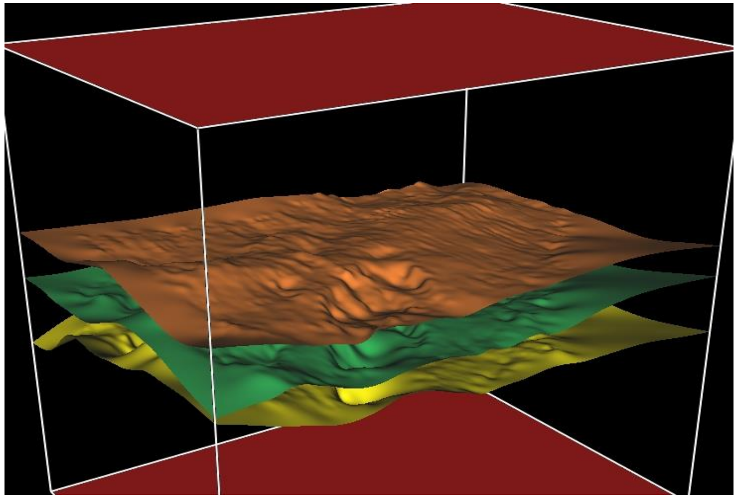


Figure G.1 - Construction of the structural model

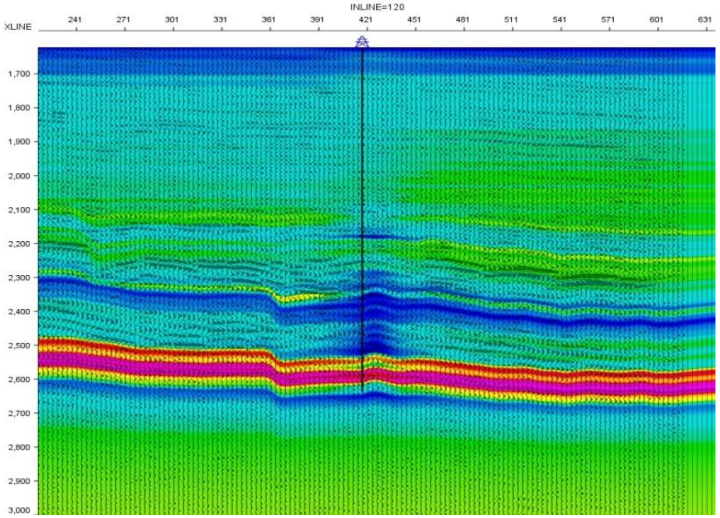
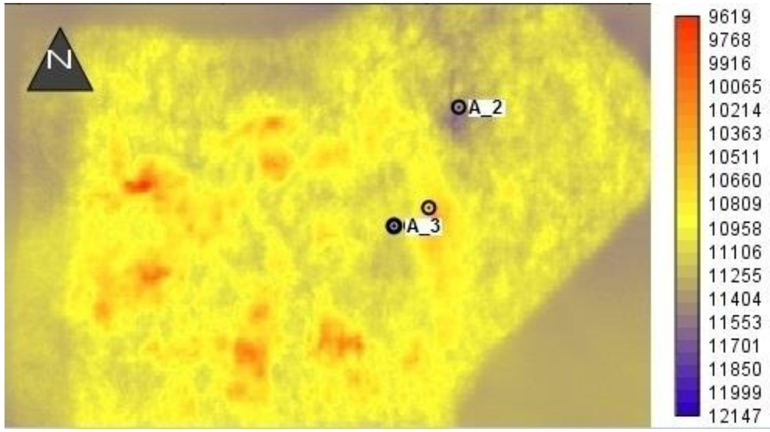


Figure G.2 - A priori structural model



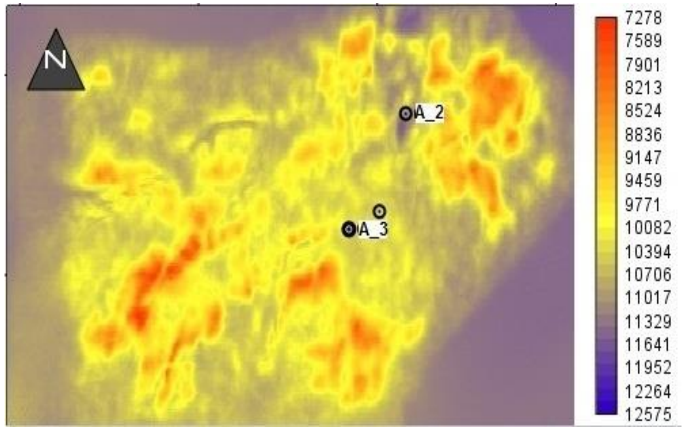


Figure G.3 - Impedance map after inversion over horizon J-XIII

Figure G.4 - Impedance map after inversion over horizon V

Attachment H

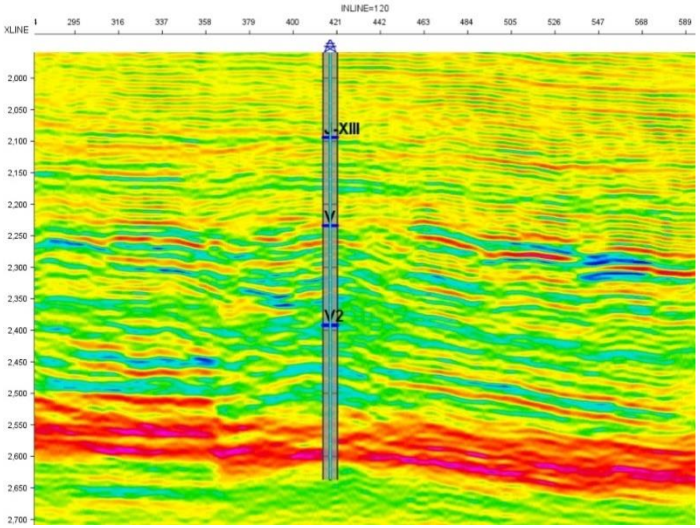


Figure H.1 - Impedance section after inversion on well D

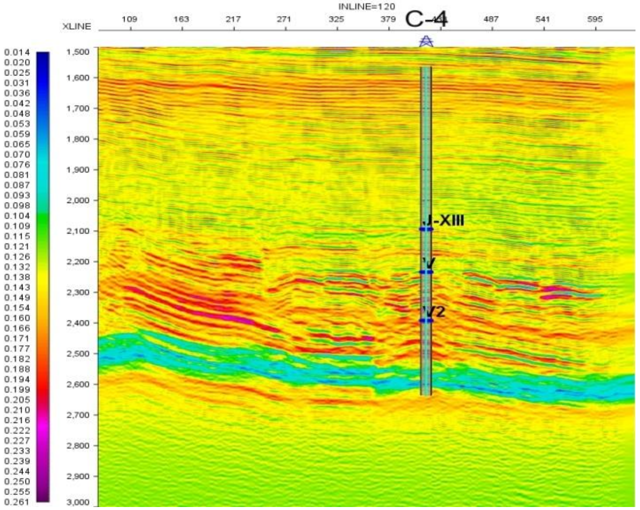
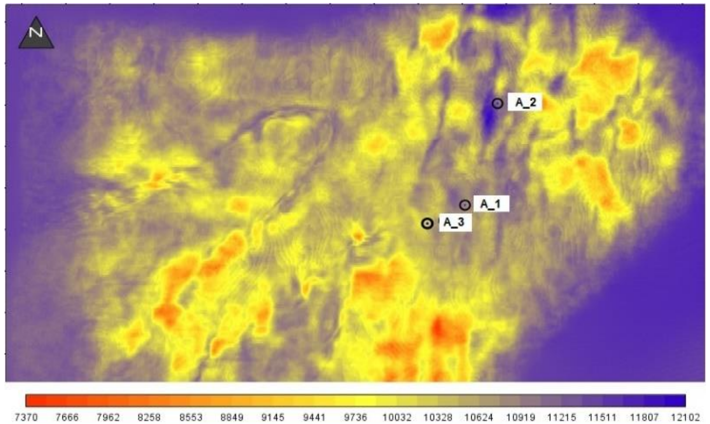


Figure H.2 - Pseudo-porosity section at well A



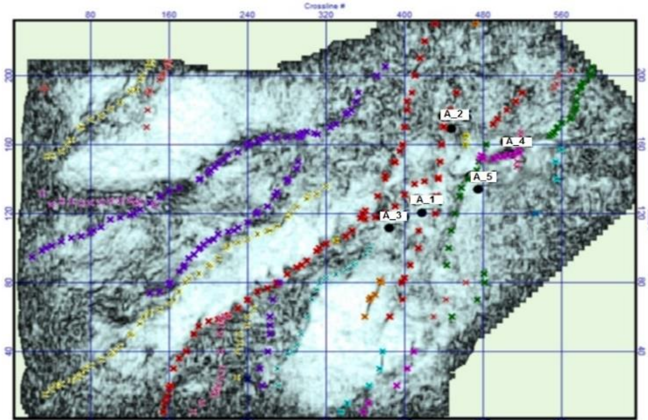
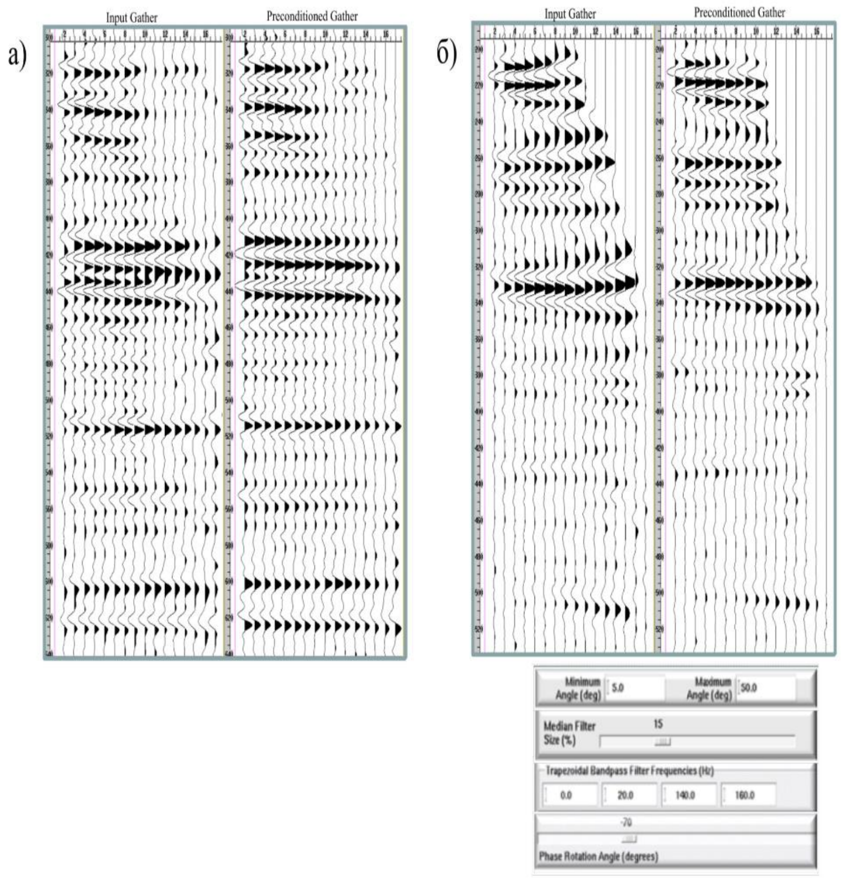


Figure H.3 - Map of Impedances between Horizons J1 and T3

Figure H.4 - Coherence cube

Attachment I



Minimum Angle (deg) 5.0
Maximum Angle (deg) 50.0
Median Filter Size (%) 15
Trapezoidal Bandpass Filter Frequencies (Hz) 0.0 20.0 140.0 160.0
-70 Phase Rotation Angle (degrees)

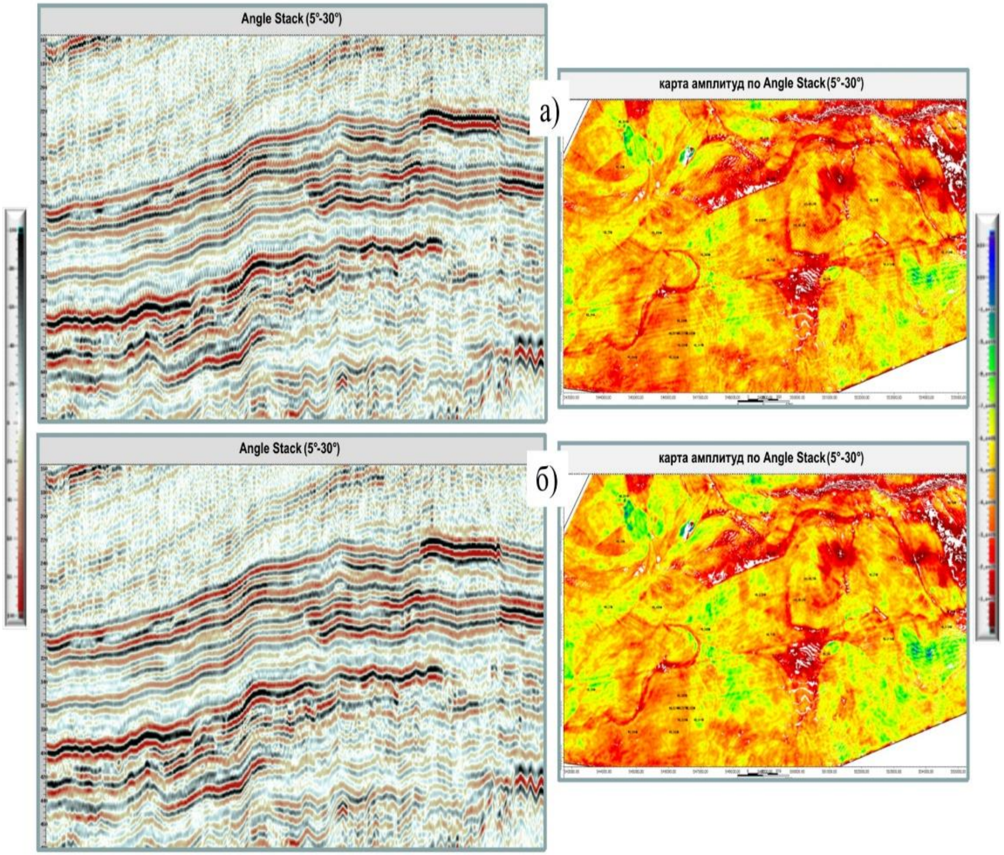


Figure I.1 - Comparison of initial gathers and gathers after preliminary processing

Figure I.2 - Section of partial angular sum 5°-30°, as well as a map of minimum amplitude values for this cube, taken along the NeoA1 horizon.

Attachment J

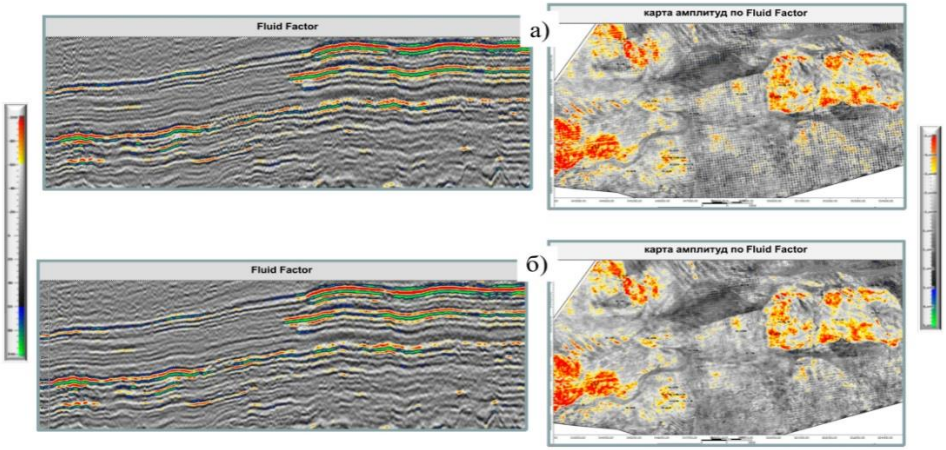


Figure J.1 - Example of a time section of a Fluid Factor AVO attribute and its amplitude distribution before (a) and after (b) migration noise subtraction

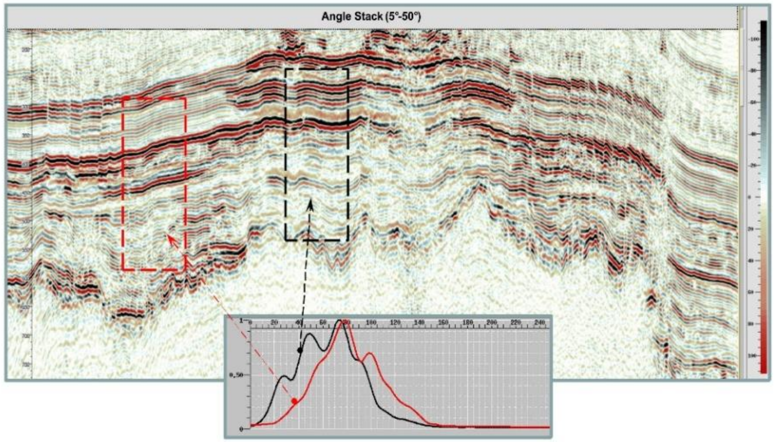


Figure J.2 - Example of influence of gas on seismic data

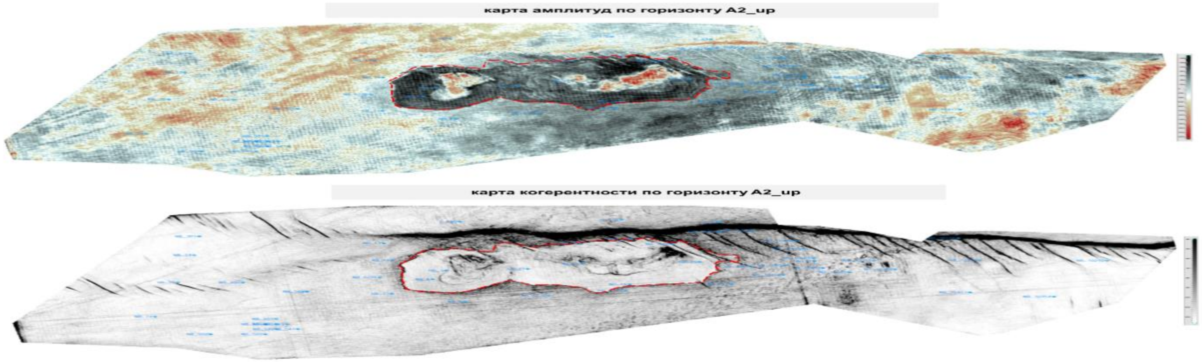


Figure J.3 - amplitude and coherence maps taken along horizon A2_up

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