Method and Apparatus for Determining Thin Interlayers

This application claims priority of the Chinese Patent Application with the application number 201710890153.1, filed on September 27, 2017, and entitled "Methods and Apparatus for Determining Thin Interlayers", the entire contents of which are incorporated herein by reference.

Technical Field

The present application relates to the technical field of oil and gas exploration, in particular to a method and an apparatus for determining thin interlayers.

Background

In the exploration and development of shale gas, because of the characteristics of shale gas itself, most of the shale gas will occur in a shale section in the form of a free state or an adsorbed state. The study shows that a thin interlayer of a carbonate rock in the shale section is helpful to strengthen reconstructability of a reservoir in the shale section, and plays an important role in the concrete exploration and development of shale gas.

At present, in order to identify and determine the thin interlayer in a target area, generally one-dimensional lithologic proportion and two-dimensional facies control are used as constraints to perform inversion to determine the concrete thin interlayer. However, limited by the method itself, the specific implementation can only make the inversion result present a horizontal change trend, but cannot distinguish the longitudinal variation characteristics. Furthermore, the resolution of the obtained inversion result is low, and the recognition accuracy is poor for thin interlayers having relatively thin thickness among the thin interlayers (i.e., thin interlayers having a single layer thickness of 0.5-1.5 meters). In summary, in specific implementation, the existing methods often have technical problems that determination of thin interlayers has a large error and resolution is low.

Regarding the above technical problem, no effective solution has been proposed yet.

Summary of the Invention

Embodiments of the present application provide a method and an apparatus for determining thin interlayers to solve the technical problems of the existing methods that determination of thin interlayers has a large error and resolution is low, to achieve the technical effect of not only reflecting longitudinal change trend characteristics but also

reflecting horizontal change trend characteristics, thereby being possible to determine thin interlayers more precisely.

Embodiments of the present application provide a method of determining thin interlayers, comprising:

acquiring logging data, core testing analysis data, seismic pre-stack gather data, seismic stack migration data and seismic interpretation horizon data of a target area;

determining a high-frequency three-dimensional lithologic probability volume of a thin interlayer based on the logging data, the core testing analysis data, the seismic stack migration data and seismic interpretation horizon data, wherein the high-frequency three-dimensional lithologic probability volume serves as an input to pre-stack geostatistical inversion and is a high-frequency lithology probability volume established by utilizing logging data and seismic data, wherein a frequency band of the high-frequency three-dimensional lithologic probability volume exceeds the dominant bandwidth range of the seismic data;

determining the thin interlayer in the target area by the pre-stack geostatistical inversion, using the high-frequency three-dimensional lithologic probability volume of the thin interlayer as a constraint.

In an embodiment, the frequency band of the high-frequency three-dimensional lithologic probability volume is 60-500 Hz.

In an embodiment, the determining a high-frequency three-dimensional lithologic probability volume of a thin interlayer in a target area based on the logging data, the core testing analysis data, the seismic stack migration data and seismic interpretation horizon data, includes:

determining a first high-frequency probability volume with respect to distribution of thin interlayers based on the logging data, the core testing analysis data, and the seismic interpretation horizon data;

determining a second high-frequency probability volume with respect to distribution of thin interlayers based on the logging data, the seismic stack migration data, and the seismic interpretation horizon data;

determining a high-frequency three-dimensional lithologic probability volume of the thin interlayer based on the first high-frequency probability volume and the second high-frequency probability volume.

In an embodiment, the determining a first high-frequency probability volume with respect to distribution of thin interlayers based on the logging data, the core testing analysis data, and the seismic interpretation horizon data, includes:

determining a logging response characteristic of the interlayer through logging evaluation according to the logging data;

obtaining petrophysical analysis result data through petrophysical analysis according to the logging data;

establishing a probability curve of distribution of on-well interlayers within a target horizon according to the petrophysical analysis result data, the logging response characteristics, and the core testing analysis data;

obtaining the first high-frequency probability volume with respect to distribution of thin interlayers by inter-well interpolation of the probability curve of distribution of on-well interlayers within the target horizon, according to the logging response characteristic of the interlayer based on the petrophysical analysis result.

In an embodiment, the determining a second high-frequency probability volume with respect to distribution of thin interlayers based on the logging data, the seismic stack migration data, and the seismic interpretation horizon data, includes:

performing a seismic waveform difference simulation on the seismic stack migration data by utilizing the probability curve of distribution of on-well interlayers, to obtain the second high-frequency probability volume with respect to distribution of thin interlayers.

In an embodiment, the determining a high-frequency three-dimensional lithologic probability volume of the thin interlayer based on the first high-frequency probability volume and the second high-frequency probability volume, includes:

fusing the first high-frequency probability volume and the second high-frequency probability volume in a frequency domain to obtain a high-frequency three-dimensional lithologic probability volume of the thin interlayer.

In an embodiment, using the high-frequency three-dimensional lithologic probability volume of the thin interlayer as a constraint, determining the thin interlayer in the target area by the pre-stack geostatistical inversion, includes:

performing gather processing on the seismic pre-stack gather data to obtain partial stack migration data and full stack migration data;

using the high-frequency three-dimensional lithologic probability volume of the thin interlayer as a constraint, determining the thin interlayer in the target area by the pre-stack geostatistical inversion, based on the partial stack migration data and the full stack migration data.

In an embodiment, the gather processing includes at least one of:

de-noising process, residual static correction process, multiple wave attenuation process,

gather flattening process, gather removing process, and stack process.

In an embodiment, using the high-frequency three-dimensional lithologic probability volume of the thin interlayer as a constraint, determining the thin interlayer in the target area by the pre-stack geostatistical inversion, based on the partial stack migration data and the full stack migration data, includes:

using the high-frequency three-dimensional lithologic probability volume of the thin interlayer as a constraint, performing pre-stack geostatistical inversion on the partial stack migration data and the full stack migration data to determine an inversion result, wherein the inversion result includes a P-wave impedance data volume, the ratio of compressional wave velocity to shear wave velocity data volume, and a density data volume;

determining the thin interlayer in the target area based on the inversion result.

In an embodiment, after determining the thin interlayer in the target area, the method further comprises:

directing shale gas exploration of the target area according to the thin interlayer.

Embodiments of the present application further provide an apparatus of determining thin interlayers, comprising:

an acquisition module for acquiring logging data, core testing analysis data, seismic pre-stack gather data, seismic stack migration data and seismic interpretation horizon data of a target area;

a first determination module for determining a high-frequency three-dimensional lithologic probability volume of a thin interlayer based on the logging data, the core testing analysis data, the seismic stack migration data and seismic interpretation horizon data, wherein the high-frequency three-dimensional lithologic probability volume serves as an input to pre-stack geostatistical inversion and is a high-frequency lithology probability volume established by utilizing logging data and seismic data, wherein a frequency band of the high-frequency three-dimensional lithologic probability volume exceeds the dominant bandwidth range of the seismic data;

a second determination module for using the high-frequency three-dimensional lithologic probability volume of the thin interlayer as a constraint, determining the thin interlayer in the target area by the pre-stack geostatistical inversion.

In an embodiment, the first determination module includes:

a first determination unit for determining a first high-frequency probability volume with respect to distribution of thin interlayers within a target horizon based on the logging data and the core testing analysis data;

a second determination unit for determining a second high-frequency probability volume with respect to distribution of thin interlayers based on the logging data, the seismic stack migration data, and the seismic interpretation horizon data;

a third determination unit for determining a high-frequency three-dimensional lithologic probability volume of the thin interlayer based on the first high-frequency probability volume and the second high-frequency probability volume.

In an embodiment, the second determination module includes:

a processing unit for performing gather processing on the seismic pre-stack gather data to obtain partial stack migration data and full stack migration data;

a fourth determination unit for using the high-frequency three-dimensional lithologic probability volume of the thin interlayer as a constraint, determining the thin interlayer in the target area by the pre-stack geostatistical inversion, based on the partial stack migration data and the full stack migration data.

In the embodiments of the present application, firstly the high-frequency three-dimensional lithologic probability volume of the thin interlayer having a high resolution and a good characterization effect and being capable of reflecting the longitudinal change trend is determined by comprehensively utilizing the logging data and the seismic data; then the specific thin interlayer is determined by the pre-stack geostatistical inversion, using the above described high-frequency three-dimensional lithologic probability volume of the thin interlayer as a constraint, so as to solve the technical problems of the existing methods that determination of thin interlayers has a large error, the resolution is low and circle phenomenon occurs around well points, to achieve the technical effect of not only reflecting longitudinal change trend characteristics but also reflecting horizontal change trend characteristics, thereby being possible to determine thin interlayers more precisely.

Brief Description of the Drawings

To illustrate more clearly the embodiments of the present application or the technical schemes of the prior art, a brief description of the accompanying drawings in the embodiments or the prior art will be given below. Obviously, the accompanying drawings described below are only some embodiments described in this application. For those of ordinary skill in the art, other drawings can also be obtained without any creative labor from these drawings.

FIG. 1 is a process flowchart of a method of determining thin interlayers according to an embodiment of the present application;

FIG. 2 is diagram showing composition structure of an apparatus for determining thin

interlayers according to an embodiment of the present application;

FIG. 3 is a schematic diagram of playback of a well A logging curve acquired in one scenario example;

FIG. 4 is a schematic diagram of seismic stack migration data across well A and composite records acquired in one scenario example;

FIG. 5 is a schematic diagram of a target area multi-well wavelet acquired in one scenario example;

FIG. 6 is a schematic diagram of a sectional view (top) and a plan view (bottom) of inversion obtained from geostatistics applying conventional logging constraints in one scenario example;

FIG. 7 is a schematic cross-sectional view of a high-frequency three-dimensional lithologic probability volume obtained by applying the method and the apparatus of determining thin interlayers according to the embodiments of the present application in one scenario example

FIG. 8 is a schematic diagram of an inversion effect map using conventional geostatistics in one scenario example;

FIG. 9 is a schematic diagram of a pre-stack geostatistical inversion of the high-frequency three-dimensional lithologic probability volume constraints obtained using the method and the apparatus of determining thin interlayers according to the embodiments of the present application in one scenario example;

FIG. 10 is a schematic cross-sectional view showing results of probability inversion of a final calcareous interlayer (or a limestone interlayer) across a well over the whole area obtained by applying the method and the apparatus of determining thin interlayers according to the embodiments of the present application in one scenario example;

FIG. 11 is a schematic diagram of analysis of elastic parameter characteristics of four kinds of lithology in a target area obtained using the method and the apparatus of determining thin interlayers according to the embodiments of the present application; and

FIG. 12 is a quantitative interpretation template of the elastic parameter characteristics of four kinds of lithology in a target area obtained using the method and the apparatus of determining thin interlayers according to the embodiments of the present application.

Detailed Description of the Preferred Embodiment

In order to make those skilled in the art better understand the technical solutions in the present application, the technical solutions in the embodiments of the present application will

be clearly and completely described in the following with reference to the accompanying drawings in the embodiments of the present application. Obviously, the described embodiments are only a part of the embodiments of the present application, but not all of them. Any other embodiment obtained by those skilled in the art based on the embodiments of the present application without paying any creative labor should fall within the protection scope of the present application.

Considering that most of the existing methods do not fully combine the advantages of logging data with the advantages of seismic data, but the exsiting methods simply perform inversion using two-dimensional facies control as a constraint to determine the thin interlayer in a target area. Therefore, in specific implementation, usually the inversion result can only have a horizontal change trend and cannot show a longitudinal change characteristic, and the resolution of the obtained inversion result is relatively low, a circle phenomenon easily occurs at the well points, and for thinner thin interlayers (for example, thin interlayers having a thickness of 0.5 m to 1.5 m) among the thin interlayers, the recognition accuracy is relatively low, and the error is relatively large. In summary, in specific implementation, the existing methods often have technical problems that determination of thin interlayers has a large error and resolution is low. In view of the root cause of the above problems, in the present application, the high-frequency three-dimensional lithologic probability volume of the thin interlayer having a high resolution and a good characterization effect and being capable of reflecting the longitudinal change trend can be determined by comprehensively utilizing the logging data and the seismic data; then the specific thin interlayer is determined using the above described high-frequency three-dimensional lithologic probability volume of the thin interlayer, rather than two-dimensional low-resolution data, as a constraint, so as to solve the technical problems of the existing methods that determination of thin interlayers has a large error, the resolution is low, thereby achieving the technical effects of reflecting longitudinal change trend characteristics and accurately determining thin interlayers.

Based on the above thinking, embodiments of the present application provide a method of determining thin interlayers. Referring specifically to FIG. 1, which is a process flowchart of a method of determining thin interlayers according to an embodiment of the present application. In specific implementation, the method of determining thin interlayers according to an embodiment of the present application may comprise the following steps:

S1: acquiring logging data, core testing analysis data, seismic pre-stack gather data, seismic stack migration data and seismic interpretation horizon data of a target area.

In the present embodiment, the target area may specifically be a region where a shale

section exists. Most of the shale gas will occur in a free state or an adsorbed state in organic-rich shale sections. Specifically, under the formation conditions, the matrix permeability of the shale section is generally less than or equal to $0.001\times10^{-3}um^2$. Usually, the shale section is mainly rich in matrix, and may contain thin interlayers of carbonate rocks and other materials, also called thin interlayers of limestone or calcareous interlayers. The thin interlayers are helpful to strengthen reconstructability of a shale gas reservoir in the target area, and are conducive to the specific exploration and development of the shale gas. It is to be added that the aforementioned thin interlayers are divided into conventional thin interlayers and ultra-thin thin interlayers (i.e., thin interlayers thinner than the conventional thin interlayers), wherein the thickness of the ultra-thin thin interlayers may specifically be 0.5 m to 1.5 m. The existing method of determining thin interlayers is limited by the method itself, resulting in low resolution and poor accuracy, and often cannot accurately recognize the above-mentioned ultra-thin thin interlayers. In addition, there is a certain error in recognizing conventional thin interlayers. In addition to being applicable to determining ultra-thin thin interlayers, the method of determining thin interlayers according to the embodiments of the present application is also applicable to determining conventional thin interlayers.

In this embodiment, the aforementioned logging data may specifically be a kind of logging data. In specific implementation, the logging data can be obtained by logging in the target area. Specifically, the aforementioned logging data may specifically include a logging curve, a logging response characteristic parameter, and the like.

In this embodiment, the aforementioned seismic pre-stack gather data may specifically be a kind of seismic data. In specific implementation, the seismic pre-stack gather data can be obtained from seismic records in the target area. Specifically, the aforementioned seismic pre-stack gather data may be a CRP (common reflection point) gather. It should be noted that the aforementioned seismic pre-stack gather data includes seismic pre-stack gather data of the area where a logging well corresponding to the aforementioned logging data is.

In this embodiment, the aforementioned seismic stack migration data may specifically be a kind of seismic data. In specific implementation, the seismic interpretation result can be obtained according to the seismic data. The aforementioned seismic stack migration data may specifically be a kind of data in the seismic interpretation results. It should be noted that the aforementioned seismic stack migration data passes through the area where a logging well corresponding to the aforementioned logging data is.

In this embodiment, the aforementioned core testing analysis data may specifically be

data obtained by performing a specific core testing analysis on a core sample collected in a target area. The aforementioned seismic interpretation horizon data may specifically be a kind of seismic data for representing relevant information of the seismic horizon.

In this embodiment, it should be noted that there are only a limited number of logging wells in the target area, and the geological structure of the area where the logging wells are located can be well reflected by the logging data of the aforementioned logging wells, but the geological structure of areas having no logging wells cannot be determined directly according to the logging data. In contrast, the aforementioned seismic data can better reflect relevant information of individual positions in the target area, but the effect of characterization is not as fine as that of the logging data. In that present embodiment, therefore, in order to accurately determine the thin interlayer in the target area, logging data, such as logging data, and seismic data, such as seismic stack migration data and seismic pre-stack gather data, may be combined to comprehensively utilize advantages of the two types of data, to characterize the specific geological condition of the individual positions in the target are more accurately, and to precisely determine the thin interlayers in the target area.

S2: determining a high-frequency three-dimensional lithologic probability volume of a thin interlayer based on the logging data, the core testing analysis data, the seismic stack migration data and seismic interpretation horizon data.

The high-frequency three-dimensional lithologic probability volume serves as an input to pre-stack geostatistical inversion and is a high-frequency lithology probability volume established by utilizing logging data and seismic data, wherein a frequency band of the high-frequency three-dimensional lithologic probability volume exceeds the dominant bandwidth range of the seismic data.

In an embodiment, the frequency band of the high-frequency three-dimensional lithologic probability volume is 60-500 Hz.

The high-frequency three-dimensional lithologic probability volume is used as an input of geostatistical random inversion, which can make the geostatistical inversion result more spatially and geologically reasonable in addition to maintaining the characteristics of the ultra-thin layer.

In an embodiment, in order to determine a high-frequency three-dimensional lithologic probability volume of the thin interlayer having a high resolution and a good characterization effect and being capable of reflecting the longitudinal change trend and having a three-dimensional characterization capability, in specific implementation, the above described determining a high-frequency three-dimensional lithologic probability volume of a thin

interlayer based on the logging data, the core testing analysis data, the seismic stack migration data and seismic interpretation horizon data may include:

S2-1: determining a first high-frequency probability volume with respect to distribution of thin interlayers within a target horizon based on the logging data and the core testing analysis data.

In this embodiment, the aforementioned core testing analysis data may specifically refer to the data for characterizing the lithology obtained by performing testing analysis of mineral content of the core sample collected in the target area.

In this embodiment, the above data for characterizing lithology can be obtained specifically by: performing testing analysis of mineral content of the core sample collected in the target area to obtain the mineral content characteristics of the core sample; explaining the lithology of a target shale section in the target area based on the characteristics of the mineral content of the core sample, and dividing the lithology of the target shale section in the target area into four kinds of lithology, namely, brittle shale, plastic shale, argillaceous limestone and limestone.

In this embodiment, in specific implementation, the lithologic division may be performed by: classifying the shale having quartz mineral content being equal to or greater than 50% and organic carbon content being equal to or greater than 4% as brittle shale; classifying the shale having carbonate mineral content being greater than 50% and clay mineral content being smaller than 20% and an effective porosity being smaller than 2% as limestone; classifying the shale having carbonate mineral content being greater than 50% and clay content being greater than 20% and an effective porosity being greater than 2% as argillaceous limestone; and classifying the remaining of the target shale section as plastic shale.

In this embodiment, after the data for characterizing the lithology is obtained, further, a lithology curve can be determined based on the mineral content characteristics of the four kinds of lithology divided in the above, which can be described as Litho1.

In this embodiment, the aforementioned logging data may specifically include a natural gamma logging curve, a sonic moveout logging curve, a neutron porosity curve, a resistivity logging curve, a density logging curve, and other logging curves.

In an embodiment, in order to be able to accurately determine the first high-frequency probability volume with respect to distribution of the thin interlayers, the specific implementation may be performed by as follows:

S2-1-1: determining a logging response characteristic of the interlayer through logging evaluation according to the logging data.

In this embodiment, the aforementioned determining a logging response characteristic of the interlayer through logging evaluation according to the logging data, may specifically include: the logging response characteristics of the interlayers with different lithologies can be determined by comprehensively comparing the curve characteristics of various logging curves. For the formation with the lithology being brittle shale, the logging response characteristics are as follows: a high natural gamma value, a high sonic moveout value, a high neutron porosity value, a high resistivity and a low density; and for the interlayer with the lithology being carbonatite, the logging response characteristics are as follows: a high resistivity, a high density, a low natural gamma value, a low sonic moveout value and a low neutron porosity, and the like.

S2-1-2: obtaining petrophysical analysis result data through petrophysical analysis according to the logging data.

In this embodiment, the above described obtaining petrophysical analysis result data through petrophysical analysis according to the logging data, may specifically include: according to the logging data, through petrophysical (characteristic) analysis, it can be found that four kinds of lithology can be effectively distinguished by intersection of a P-wave impedance and the ratio of compressional wave velocity to shear wave velocity, specifically, the interlayer of carbonate rock has the largest P-wave impedance, the stratum of brittle shale has the smallest ratio of P-wave velocity to S-wave velocity, the stratum of plastic shale has the largest ratio of P-wave velocity to S-wave velocity, and the interlayer of argillaceous limestone has the median P-wave impedance and the median ratio of P-wave velocity to S-wave velocity, i.e., the corresponding result data of petrophysical analysis is obtained. Reference can be made specifically to the related contents shown in FIGs. 11 and 12.

S2-1-3: establishing a probability curve of distribution of on-well interlayers according to the petrophysical analysis result data, the logging response characteristics, and the core testing analysis data.

In this embodiment, the above described establishing a probability curve of distribution of on-well interlayers according to the petrophysical analysis result data, the logging response characteristics, and the core testing analysis data, in specific implementation, may be performed as follows.

For the lithology curve Litho1 defined by the core mineral contents (i.e. core testing analysis data), it can be expressed as follows according to approximate normalization of each lithology of each well: Quartz content + clay content + carbonate content + organic carbon content + pore content =1. The content probability curves of the limestone and the argillaceous

limestone can be approximately represented by values of carbonate contents. The greater value of the carbonate content indicates greater probability of limestone, and the probabilities of the remaining brittle shale and plastic shale are approximately values obtained by subtracting the probabilities of the limestone and the argillaceous limestone from 1, and then normalized according to the quartz mineral content data to the data between the aforementioned probability values obtained by subtracting the probabilities of the limestone and the argillaceous limestone from 1, such data are the probability values of the brittle shale and the plastic shale. The specific calculation formula may be expressed in the following form:

$$X = \frac{(S\text{-c})(b-a)}{d-c} + \text{c}$$

Wherein X may specifically denote the probability of the brittle shale or the plastic shale, and the greater value of X indicates the greater probability of the brittle shale; S may specifically denote the value of the quartz mineral content, a may specifically denote the minimum value of the quartz mineral content, b may specifically denote the maximum value of the quartz mineral content; c may specifically denote the minimum value of the value obtained by subtracting the probabilities of the limestone and the argillaceous limestone from 1, d may specifically denote the maximum value of the value obtained by subtracting the probabilities of the limestone and the argillaceous limestone from 1.

In this way, according to the above calculation formula, the probability values of four kinds of lithology in the longitudinal direction of each well can be obtained after standardized processing of the carbonate mineral content and the quartz mineral content, and specifically, a lithology probability curve can be formed for each well, i.e., probability curves from which distribution of the on-well interlayers is obtained can be established. Specifically, for the lithology curve Litho1 defined by the core mineral contents, a second method may also be used, that is, normalization processing is performed separately according to the thickness of each lithology, that is, the proportion of each lithology to the total thickness of the section is determined and set as the probability value of distribution of the lithology, then the probability values of four kinds of lithology occupying the section are calculated respectively for each well in the longitudinal direction, such that a lithology probability curve can be formed for each well.

S2-1-4: obtaining the first high-frequency probability volume with respect to distribution of thin interlayers by inter-well interpolation of the probability curve of distribution of on-well interlayers, according to the logging response characteristic of the interlayer based on the petrophysical analysis result.

In this embodiment, the above described inter-well interpolation may also be referred to as an inter-well difference method, and in specific implementation, inter-well difference may be performed by utilizing inverse distance weighting or a simple Kriging method to obtain the first high-frequency probability volume of the distribution of the four kinds of lithology in the target area, respectively, that is, the first high-frequency probability volume with respect to distribution of thin interlayers.

S2-2: determining a second high-frequency probability volume with respect to distribution of thin interlayers based on the logging data and the seismic stack migration data.

In an embodiment, in specific implementation, the determining a second high-frequency probability volume with respect to distribution of thin interlayers based on the logging data and the seismic stack migration data, may be performed as follows: based on the logging data and numerical results of distribution of the lithologies explained for the well, a curve of results of the lithologies for distribution of on-well interlayers is obtained, including four kinds of lithology, namely, brittle shale, plastic shale, argillaceous limestone and limestone, which can be denoted by 1, 2, 3 and 4 respectively; then a seismic waveform indication simulation (or called waveform difference simulation) on the seismic stack migration data based on the above described the probability curve of distribution of on-well interlayers, to obtain the second high-frequency probability volume with respect to distribution of thin interlayers.

In this embodiment, specific implementation can be carried out by performing a seismic waveform indication simulation on the seismic stack migration data utilizing the curve of results of the lithologies for distribution of on-well interlayers, to obtain the second high-frequency probability volume with respect to distribution of thin interlayers.

According to the logging data and the petrophysical analysis result data, optimizing can be made continuously under the guidance of seismic waveform data in the target section. Specifically, all wells can be sorted according to correlation degree with reference to two factors including well point sample distribution distance and seismic waveform characteristics, and the wells with high correlation degree with prediction points are preferred as an initial model to carry out unbiased optimal estimation of high frequency components of the wells, and the finally simulated lithologic probability distribution is ensured to be consistent with the original seismic waveform. The mechanism of the above described implementation is based on well-seismic co-simulation with relative change of waveform.

Specifically, a variable variance attribute of the seismic waveform is used as a feature vector describing the waveform change of the seismic wave. Statistics of variable variance parameters of different lithologies of drilled byways is performed to represent the

"contribution" of vertical structural change of well lithology to the change of the seismic waveform. Statistics of the feature vector of the seismic waveform of the predicted shaft is performed, and the lithology probability of the predicted shaft well is simulated by utilizing a variable variance function to obtain the aforementioned second high-frequency probability volume.

For example, the probability volume of the limestone of the predicted shaft is simulated for the target area using a variable variance function of the seismic waveform of the longitudinal limestone position after the drilled well has been subjected to well seismic calibration, as a feature vector. In the same way, the probability volume of the argillaceous limestone of the predicted shaft is simulated by using a variable variance function of the seismic waveform at the location of the argillaceous limestone on the well as a feature vector. Then, the probability volume of the brittle shale of the predicted shaft is simulated by using a variable variance function of the seismic waveform at the location of the brittle shale on the well as a feature vector. Finally the probability volume of the plastic shale is calculated according to the following formula, to obtain the final second high-frequency probability volume:

1 - the probability volume of the limestone - the probability volume of the argillaceous limestone - the probability volume of the brittle shale.

In this embodiment, the above described variable variance may specifically refer to relationship between an amplitude of an adjacent sampling point in the same time window and a previous sampling point and a variance of individual sampling points in the time window, and may be used to describe an amount of amplitude change. The calculation formula can be specifically expressed in the following form:

$$SN = \sqrt{\frac{r(h-1) + r(h)}{2} - S}$$

$$S = \frac{1}{N-1}\sum_{i=1}^{N}\left[x(i) - \bar{x}\right]^2$$

wherein, $r(h) = \frac{1}{N(h)}\sum_{i=1}^{N(h)}\left[x(i) - x(i+h)\right]^2$ may specifically denote a mean value of sum of squares of the amplitude differences of two sampling points with the same time window interval *h*, N(h) may specifically denote the number of sampling points with the time window interval h-1, and the variance S may specifically denote the extent to which the amplitude of the sampling point deviates from its mean value, SN may specifically denote the

variance of adjacent two sampling points in the sane time window, X(i) may specifically denote an amplitude value of a sampling point numbered i, i may specifically denote the number of the sampling point, and h may specifically denote a sampling interval.

Furthermore, the lithologic distribution of known wells can be analyzed according to the seismic waveform characteristics, and well samples having high correlation with the waveform of the shaft to be discriminated are preferred to establish an initial model, and statistics is done of the lithologic results of the well samples that are used as prior information. The wells having similar waveforms among the known wells are preferred as spatial estimation samples, by double variants including waveform similarity, difference and spatial distance. Then the lithologic results on the initial well are matched with the variable variance parameters of the seismic waveform for filtering, to perform calculation to obtain a likelihood function. If the seismic waveforms of the two wells are similar, it indicates that the large lithologies of the two wells are similar, then the high frequency range can be restricted by such characteristic, such that the lithology probability simulation result is more determinate, so as to improve accuracy of the obtained second high-frequency probability volume.

In this embodiment, considering that a variation function of the well lithology result is often used in establishing the initial model in the existing method, which may be affected by the well location distribution, so that it is difficult to accurately characterize the heterogeneity of the lithology distribution, and the densely distributed seismic waveform can accurately characterize changes in spatial structure and lithology. Therefore, the initial model can be established by using the characteristics of the seismic waveform and combining an effective sample, a smooth radius, a target sampling rate and other data, by establishing a reasonable stratigraphic framework model and completing the well seismic calibration of the synthetic records of wells in the target area.

In this embodiment, the effective sample number may be one of the very important parameters in the seismic waveform indication simulation, and is mainly used to characterize the degree of influence of the spatial variation of the seismic waveform on the lithology. The setting of the parameter is made mainly with reference to the results of statistics of the known wells. Specifically, statistical analysis can be conducted using "the sample number" and "seismic correlation", the correlation gradually increases with the increase of the sample number, and the correlation does not increase with the increase of the sample number after it reaches a certain degree, which indicates that more samples do not contribute to improvement of prediction accuracy, and the number of samples when the correlation is highest is the best sample parameter. The number of samples may generally be set to 5. Furthermore, the

parameter is also related to the total number of samples. In general, the large number of samples indicates small variation of lithology probability and weak heterogeneity, and the number of samples can be reduced appropriately in areas where lcateral variation is rapid and heterogeneity is strong.

In this embodiment, the value range of the above described smooth radius is greater than or equal to 0, and is smaller than or equal to 5. In this embodiment, it may be specifically set to 1. Generally, the larger the smooth radius is, the better the lateral continuity of the obtained lithology probability distribution data volume is. If the lithology of the target area changes rapidly laterally and has a narrow width, the smooth radius may be 1.

In this embodiment, the demand for accurate prediction of shale thin interlayers in the target area can be met if the numerical value of the above described target sampling rate is smaller, the resolution of the simulated lithology probability result is higher, the data volume is smoother, the calculation time is longer, and the on-well lithology thickness is smaller (for example, 0.2 ms).

S2-3: determining a high-frequency three-dimensional lithologic probability volume of the thin interlayer based on the first high-frequency probability volume and the second high-frequency probability volume.

In an embodiment, in order to determine the high-frequency three-dimensional lithologic probability volume of the thin interlayer having a high resolution and a good characterization effect and being capable of reflecting the longitudinal change trend, in specific implementation, the above described determining a high-frequency three-dimensional lithologic probability volume of the thin interlayer based on the first high-frequency probability volume and the second high-frequency probability volume may include: fusing the first high-frequency probability volume and the second high-frequency probability volume through a global Kriging method in a frequency domain to obtain a high-frequency three-dimensional lithologic probability volume of the thin interlayer.

In an embodiment, in specific implementation, the above described fusing the first high-frequency probability volume and the second high-frequency probability volume to obtain a high-frequency three-dimensional lithologic probability volume of the thin interlayer may include: determining a first weight of the first high-frequency probability volume by combining fluctuation characteristics of the stratum in the target area according to the frequency of the first high-frequency three-dimensional lithologic probability volume; determining a second weight of the second high-frequency probability volume by combining fluctuation characteristics of the stratum in the target area according to the frequency of the

second high-frequency three-dimensional lithologic probability volume; combining the product of the first high-frequency probability volume and the first weight with the product of the second high-frequency probability volume and the second weight, to obtain the high-frequency three-dimensional lithologic probability volume of the thin interlayer. That is, the fusion of the first high-frequency probability volume with the second high-frequency probability volume is completed. Subsequently, the result data obtained by fusing the first high-frequency probability volume with the second high-frequency probability volume as described in the above can be used as a constraint condition, and the elastic parameter data such as the high resolution P-wave impedance and the ratio of compressional wave velocity to shear wave velocity can be better obtained by inversion.

In this embodiment, the aforementioned fluctuation characteristics of the stratum in the target area may be specifically determined according to the stack migration horizon data. Specifically, when the degree of formation fluctuation characterized by the determined fluctuation characteristics of the stratum in the target area is relatively large, the specific value of the second weight may be appropriately increased; and correspondingly, when the degree of formation fluctuation characterized by the determined fluctuation characteristics of the stratum in the target area is relatively small, the specific value of the second weight may be appropriately decreased. The specific value of the first weight may be appropriately decreased while the specific value of the second weight is increased; and correspondingly, the specific value of the first weight may be appropriately increased while the specific value of the second weight is decreased. Specifically, for example, the first weight may be 0 and the second weight may be 1 when the degree of formation fluctuation characterized by the determined fluctuation characteristics of the stratum in the target area is very large and exceeds the threshold value. In this case, the high-frequency three-dimensional lithologic probability volume of the thin interlayer obtained by fusing the first high-frequency probability volume with the second high-frequency probability volume corresponds to the second high-frequency probability volume used alone.

In this embodiment, in specific implementation, considering that the first high-frequency probability volume is obtained by inter-well interpolation, when the formation is horizontal, has a small dip angle and a large number of wells, the formation morphology changes little (i.e., the degree of formation fluctuation is relatively small), the first high-frequency probability volume may be used; when the formation morphology changes greatly (i.e., the degree of formation undulation is relatively large), the second high-frequency probability volume may be used, this is because the second high-frequency probability volume is realized

by inter-well simulation by taking into account the variation characteristics of the horizontal seismic waveform. Without doubt, data volumes of the two high-frequency probability volumes may be combined in the frequency domain according to the specific situation, so as to further improve the effect of the simulated lithologic probability volume.

In this embodiment, as compared with the first high-frequency probability volume and the second high-frequency probability volume, the high-frequency three-dimensional lithologic probability volume of the thin interlayer obtained by the above-mentioned method has relatively good consistency with the well points of the logging well, and also truly reflects spatial variation of the thin interlayer in the formation environment, thus the advantages of different data such as logging data and seismic data are well integrated, which can not only reflect the characteristics of horizontal change trend, but also reflect the characteristics of vertical change trend, has a higher resolution, and can accurately and finely reflect the specific structural conditions of the formation in the area where the thin interlayer is.

S3: using the high-frequency three-dimensional lithologic probability volume of the thin interlayer as a constraint, determining the thin interlayer in the target area by the pre-stack geostatistical inversion.

In an embodiment, in order to determine the thin interlayer in the target area accurately, in specific implementation, the above described using the high-frequency three-dimensional lithologic probability volume of the thin interlayer as a constraint, determining the thin interlayer in the target area by the pre-stack geostatistical inversion, may specifically include:

S3-1: performing gather processing on the seismic pre-stack gather data to obtain partial stack migration data and full stack migration data;

S3-2: using the high-frequency three-dimensional lithologic probability volume of the thin interlayer as a constraint, determining the thin interlayer in the target area by the pre-stack geostatistical inversion, based on the partial stack migration data and the full stack migration data.

In an embodiment, in order to be able to obtain the partial stack migration data and the full stack migration data that meet construction requirements, in specific implementation, the gather processing may specifically include at least one of de-noising process, residual static correction process, multiple wave attenuation process, gather flattening process, gather removing process, and stack process, and etc. Without doubt, it should be noted that the above listed several types of gather processing are only for better description of the embodiments of the present application, and other types of gather processing may also be introduced according to specific conditions and construction requirements in specific implementation.

In an embodiment, in order to determine the thin interlayers accurately, in specific implementation, the above described using the high-frequency three-dimensional lithologic probability volume of the thin interlayer as a constraint, determining the thin interlayer in the target area by the pre-stack geostatistical inversion, based on the partial stack migration data and the full stack migration data, may include:

S3-2-1: using the high-frequency three-dimensional lithologic probability volume of the thin interlayer as a constraint, performing pre-stack geostatistical inversion on the partial stack migration data and the full stack migration data to determine an inversion result, wherein the inversion result includes a P-wave impedance data volume, the ratio of compressional wave velocity to shear wave velocity data volume, and a density data volume.

In this embodiment, the aforementioned pre-stack geostatistical inversion may specifically be a way of implementation which obtains a series of high-resolution reservoir properties by combining a conventional geostatistical simulation technique with Bayesian inference, Monte Carlo simulation of Markov chains, and a pre-stack simultaneous inversion technique. This way of implementation reasonably predicts the uncertain solution set space of the reservoir model by synthesizing various information sources (including geological, seismic and logging information, etc.). The pre-stack geostatistical inversion can effectively improve the inversion resolution, accurately describe the spatial distribution of reservoir lithology and distribution of physical properties, and reliably depict the spatial distribution of reservoir lithology and physical properties.

In specific implementation, the key to the implementation of the above-mentioned pre-stack geostatistical inversion is that the composite records obtained from the inversion of P-wave impedance and S-wave impedance and wavelet convolution are matched with the seismic data. Therefore, before the pre-stack geostatistical inversion, a deterministic inversion is needed to ensure that the seismic information and the logging information are highly unified. Furthermore, if the input seismic data is a partial angular stack, a full Zoeppritz equation needs to be selected for performing the pre-stack geostatistical inversion. In high-resolution lithologic inversion, Markov chain - Monte Carlo simulation can be applied to simultaneously generate high-resolution rock elastic parameter bodies, and then the seismic records of various migration distances are synthesized and compared with actual seismic data to thereby control rationality of realizing a single lithology. Finally, a high-resolution lithology probability volume is obtained, and the higher the probability is, the more reliable the lithology is. Reference can be made specifically to the contents shown in FIGs. 9 and 10.

In this embodiment, in specific implementation, the pre-stack geostatistical inversion may

include the following steps:

S1: performing quality control on the partial stack migration data. To be specific, the seismic data volumes of near, medium and far migration distances may be aligned and corrected according to the reference horizon in the given time window.

S2: through well editing and well seismic calibration, a synthetic seismic record is made for seismic data volumes with different migration distances (that is, full stack migration data), and well seismic calibration is performed to obtain the integrated wavelet of multiple wells of data volumes with near, medium and far migration distances.

S3: establishing a low frequency model. Specifically, the P-wave impedance, the S-wave impedance and the density curve can be selected on the well taking the seismic horizon as a constraint, and the stratigraphic framework model can be established.

S4: performing the geostatistical inversion, which, in specific implementation, may include:

S4-1: dividing the lithology. Specifically, according to the above multi-well lithology analysis, it can be determined that the lithology of geostatistical inversion in the target area is of four types: brittle shale, plastic shale, argillaceous limestone and limestone.

S4-2: determining the percentages of the lithologies. On the basis of lithologic classification, the conventional method is to count the percentages of the four lithologies, which is also one of the important parameters of geostatistics. In this embodiment, in specific implementation, the first round of inversion may be performed at first by using the statistical lithological proportion to obtain test parameters and an inversion effect, and then the second round of inversion may be performed by using the one-dimensional statistical lithological proportion curve to obtain the test parameters and the inversion effect, and finally the high-frequency three-dimensional lithologic probability volume of the four lithologies replaces the conventional lithological proportion to serve as the constraint condition, to perform the inversion and obtain the inversion result. It should be noted that the geostatistical inversion can greatly improve the resolution of inversion by using the previously obtained high-frequency three-dimensional lithologic probability volume instead of the conventional lithological proportion as the constraint condition.

S4-3: based on the inversion result, the probability density distribution function of each lithology can be counted, the probability density function of Gaussian distribution can be selected for the types of four lithologic variation functions in the target area, and the longitudinal variation and approximate ranges of longitudinal and transverse variations can be estimated according to poststack deterministic inversion results.

S4-4: performing statistics of a variation function of each lithology, through a large number of systematic testing and analysis, variations and fitting parameters for each lithology in longitudinal (Z) and horizontal (X, Y) directions.

S4-5: testing SNR parameters, and SNR data of seismic data volumes of near, medium and far migration distances can be obtained.

After the above steps are completed, the geostatistical inversion parameters can be set to perform the geostatistical inversion to obtain inversion results, thereby obtaining the P-wave impedance, the S-wave impedance, the P-wave velocity, the S-wave velocity, density, and the ratio of compressional wave velocity to shear wave velocity data volume, etc.

S3-2-2: determining the thin interlayer in the target area based on the inversion result.

In this embodiment, the aforementioned inversion results may specifically include parameter data volumes such as a P-wave impedance, the ratio of compressional wave velocity to shear wave velocity, a density and etc. Without doubt, it should be noted that the above listed parameter data are only for better description of the embodiments of the present application, and other relevant parameter data may also be introduced according to specific conditions and construction requirements, as the aforementioned inversion results. For this point, there is no limitation in the present application.

In this embodiment, in specific implementation, the above described determining the thin interlayer in the target area based on the inversion result may include: determining that the thin interlayer of limestone in the target area is characterized by a high P-wave impedance, a high ratio of compressional wave velocity to shear wave velocity and a high density, by using the petrophysical analysis results of the thin interlayer in the target area; the P-wave impedance data volume and the ratio of compressional wave velocity to shear wave velocity data volume can be obtained by using the inversion results obtained from the pre-stack geostatistical inversion, and intersection analysis is performed on the two data volumes, and the result of intersection analysis is obtained; the data volumes of the high P-wave impedance and the high longitudinal-transverse wave velocity ratio can be further plotted according to the result of intersection analysis and the characteristics of thin interlayer, which is the data volume of the distribution of thin interlayer in limestone, so that the thin interlayer in the target area can be determined.

In this embodiment, it should be noted that based on the high-frequency three-dimensional lithologic probability volume of the thin interlayer having a high resolution and a good characterization effect and being capable of reflecting the longitudinal change trend that is used as a constraint, the inversion result obtained by the inversion has a high

longitudinal resolution, and more accords with the spatial sedimentary law, and thus can better characterize the specific formation structure in the formation where the thin interlayer is located. Furthermore, the aforementioned inversion result can be used to accurately recognize and determine the thin interlayer in the target area.

In the embodiments of the present application, compared with the prior art, the high-frequency three-dimensional lithologic probability volume of the thin interlayer having a high resolution and a good characterization effect and being capable of reflecting the longitudinal change trend is determined by comprehensively utilizing the logging data and the seismic data; then the specific thin interlayer is determined by the pre-stack geostatistical inversion, using the above described high-frequency three-dimensional lithologic probability volume of the thin interlayer as a constraint, so as to solve the technical problems of the existing methods that determination of thin interlayers has a large error, the resolution is low and circle phenomenon occurs at well points, to achieve the technical effect of not only reflecting longitudinal change trend characteristics but also reflecting horizontal change trend characteristics, thereby being possible to determine thin interlayers more precisely.

In an embodiment, in order to conduct specific exploration and development of shale gas for a target area, after determining the thin interlayer in the target area, the method may specifically further comprise: directing shale gas exploration of the target area according to the thin interlayer. Without doubt, it should be noted that use of the thin interlayer as a basis for guiding specific shale gas exploration is only one of the specific uses of thin interlayers, and in specific implementation, other corresponding geophysical exploration can be carried out using the determined thin interlayer according to the specific circumstances. For this point, there is no limitation in the present application.

It can be seen from the above description, with the method of determining thin interlayers provided according to the embodiment of the present application, the high-frequency three-dimensional lithologic probability volume of the thin interlayer having a high resolution and a good characterization effect and being capable of reflecting the longitudinal change trend is determined by comprehensively utilizing the logging data and the seismic data; then the specific thin interlayer is determined by the pre-stack geostatistical inversion, using the above described high-frequency three-dimensional lithologic probability volume of the thin interlayer as a constraint, so as to solve the technical problems of the existing methods that determination of thin interlayers has a large error and the resolution is low, to achieve the technical effect of not only reflecting longitudinal change trend characteristics but also reflecting horizontal

change trend characteristics, thereby being possible to determine thin interlayers more precisely; further, the first high-frequency probability volume with respect to distribution of thin interlayers, the second high-frequency probability volume with respect to distribution of thin interlayers are respectively determined according to the logging data and the seismic data, respectively, then the two high-frequency three-dimensional lithologic probability volumes are fused to better integrate gradients of the seismic data and the logging data to determine a high-frequency three-dimensional lithologic probability volume of the thin interlayer that has a good characterization effect and is capable of reflecting the longitudinal change trend, so as to improve accuracy of subsequent determination of the thin interlayers.

Based on the same inventive concept, embodiments of the present invention also provide an apparatus of determining thin interlayers, as described in the following embodiment. Since the principle of the apparatus to solve the problem is similar to the method of determining the thin interlayers, the implementation of the apparatus of determining the thin interlayers can be seen in the implementation of the method, and the repetitions will not be described again. As used below, the term "unit" or "module" can realize combination of software and/or hardware with predetermined functions. Although preferably the apparatus described in the following embodiment is implemented by software, implementation by hardware, or combination of software and hardware is also possible and is conceivable. Referring to FIG. 2, which showes composition structure of an apparatus for determining thin interlayers according to an embodiment of the present application, the apparatus may comprise: an acquisition module 21, a first determination module 22, and a second determination module 23, which are described in detail below.

The acquisition module 21 may specifically be used for acquiring logging data, core testing analysis data, seismic pre-stack gather data and seismic stack migration data of a target area.

The first determination module 22 may specifically be used for determining a high-frequency three-dimensional lithologic probability volume of a thin interlayer based on the logging data, the core testing analysis data, the seismic stack migration data and seismic interpretation horizon data.

The high-frequency three-dimensional lithologic probability volume serves as an input to pre-stack geostatistical inversion and is a high-frequency lithology probability volume established by utilizing logging data and seismic data, wherein a frequency band of the high-frequency three-dimensional lithologic probability volume exceeds the dominant

bandwidth range of the seismic data.

The second determination module 23 may specifically be used for using the high-frequency three-dimensional lithologic probability volume of the thin interlayer as a constraint, determining the thin interlayer in the target area by the pre-stack geostatistical inversion.

In an embodiment, in order to be capable of determining a high-frequency three-dimensional lithologic probability volume of a thin interlayer based on the logging data, the core testing analysis data, the seismic stack migration data and seismic interpretation horizon data, the first determination module 22 may specifically include the following structural units:

a first determination unit, which may specifically be used for determining a first high-frequency probability volume with respect to distribution of thin interlayers based on the logging data and the core testing analysis data;

a second determination unit, which may specifically be used for determining a second high-frequency probability volume with respect to distribution of thin interlayers based on the logging data and the seismic stack migration data;

a third determination unit, which may specifically be used for determining a high-frequency three-dimensional lithologic probability volume of the thin interlayer based on the first high-frequency probability volume and the second high-frequency probability volume.

In an embodiment, in order to be capable of determining a first high-frequency probability volume with respect to distribution of thin interlayers based on the logging data and the core testing analysis data, the aforementioned first determination unit may specifically include the following structural sub-units:

a first determining sub-unit, which may specifically be used for determining a logging response characteristic of the interlayer through logging evaluation according to the logging data;

a petrophysical analysis sub-unit, which may specifically be used for obtaining petrophysical analysis result data through petrophysical analysis according to the logging data;

an establishment sub-unit, which may specifically be used for establishing a probability curve of distribution of on-well interlayers according to the petrophysical analysis result data, the logging response characteristics, and the core testing analysis data;

an interpolation sub-unit, which may specifically be used for obtaining the first high-frequency probability volume with respect to distribution of thin interlayers by inter-well interpolation of the probability curve of distribution of on-well interlayers, according to the

logging response characteristic of the interlayer based on the petrophysical analysis result.

In an embodiment, in order to be capable of determining a second high-frequency probability volume with respect to distribution of thin interlayers based on the logging data and the seismic stack migration data, in specific implementation, the aforementioned second determination unit can perform a seismic waveform indication simulation (i.e., difference simulation) on the seismic stack migration data utilizing the probability curve of distribution of on-well interlayers, to obtain the second high-frequency probability volume with respect to distribution of thin interlayers.

In an embodiment, in order to be capable of determining a high-frequency three-dimensional lithologic probability volume of the thin interlayer based on the first high-frequency probability volume and the second high-frequency probability volume, in specific implementation, the aforementioned third determination unit can fuse the first high-frequency probability volume and the second high-frequency probability volume through a global Kriging method in a frequency domain to obtain a high-frequency three-dimensional lithologic probability volume of the thin interlayer.

In an embodiment, in order to be capable of using the high-frequency three-dimensional lithologic probability volume of the thin interlayer as a constraint, determining the thin interlayer in the target area by the pre-stack geostatistical inversion according to the seismic pre-stack gather data, the aforementioned second determination module 23 may specifically include the following structural units:

a processing unit, which may specifically be used for performing gather processing on the seismic pre-stack gather data to obtain partial stack migration data and full stack migration data;

a fourth determination unit, which may specifically be used for using the high-frequency three-dimensional lithologic probability volume of the thin interlayer as a constraint, determining the thin interlayer in the target area by the pre-stack geostatistical inversion, based on the partial stack migration data and the full stack migration data.

In an embodiment, the gather processing may specifically include at least one of de-noising process, residual static correction process, multiple wave attenuation process, gather flattening process, gather removing process, and stack process, and etc.

In an embodiment, in order to be capable of using the high-frequency three-dimensional lithologic probability volume of the thin interlayer as a constraint, determining the thin interlayer in the target area by the pre-stack geostatistical inversion, based on the partial stack migration data and the full stack migration data, the aforementioned fourth determination unit

may specifically include the following structural sub-units:

an inversion sub-unit, which may specifically be used for using the high-frequency three-dimensional lithologic probability volume of the thin interlayer as a constraint, performing pre-stack geostatistical inversion on the partial stack migration data and the full stack migration data to determine an inversion result, wherein the inversion result includes a P-wave impedance data volume, the ratio of compressional wave velocity to shear wave velocity data volume, and a density data volume;

a second determination sub-unit, which may specifically be used for determining the thin interlayer in the target area based on the inversion result.

In an embodiment, in order to be capable of conducting specific exploration and development of shale gas for a target area, in specific implementation, the aforementioned apparatus may further comprise a construction module, which may specifically be used for directing shale gas exploration of the target area according to the thin interlayer.

The various embodiments in the specification are described in a progressive manner, and the same or similar parts between the various embodiments may be referred to each other, and each embodiment focuses on the differences from the other embodiments. In particular, the system embodiment is simply described since it is substantially similar to the method embodiment, and please refer to the description of the method embodiment for the relevant content.

It should be noted that any system, apparatus, module or unit set forth in the above embodiments specifically may be implemented by a computer chip or an entity, or by a product having a certain function. For the convenience of description, herein the apparatus is described by being divided into various units based on its functions and described respectively. Without doubt, the functions of the various units may be realized in the same one or more software and/or hardware when the present application is implemented.

In addition, in the specification, the adjectives such as first and second may be only used to distinguish one element or action from another element or action, without requiring or implying any such relationship or order. Where circumstances permit, the reference to an element, or a component, or a step (and the like) should not be construed as being limited to only one element, one component or one step, but may concern one or more thereof.

It can be seen from the above description, with the apparatus of determining thin interlayers and the method of determining thin interlayers provided according to the embodiment of the present application, the high-frequency three-dimensional lithologic probability volume of the thin interlayer having a high resolution and a good characterization

effect and being capable of reflecting the longitudinal change trend is determined by comprehensively utilizing the logging data and the seismic data; then the specific thin interlayer is determined by the pre-stack geostatistical inversion, using the above described high-frequency three-dimensional lithologic probability volume of the thin interlayer as a constraint, so as to solve the technical problems of the existing methods that determination of thin interlayers has a large error and the resolution is low, to achieve the technical effect of not only reflecting longitudinal change trend characteristics but also reflecting horizontal change trend characteristics, thereby being possible to determine thin interlayers more precisely; further, the first determination unit and the second determination unit determine the first high-frequency probability volume with respect to distribution of thin interlayers, and the second high-frequency probability volume with respect to distribution of thin interlayers respectively according to the logging data and the seismic data, respectively, then the two high-frequency three-dimensional lithologic probability volumes are fused by the third determination unit to better integrate gradients of the seismic data and the logging data to determine a high-frequency three-dimensional lithologic probability volume of the thin interlayer that has a good characterization effect and is capable of reflecting the longitudinal change trend, so as to improve accuracy of subsequent determination of the thin interlayers.

In a scenario example of specific implementation, the method and the apparatus of determining thin interlayers provided by the present application are applied to specifically recognize and determine thin interlayers in a certain target area. The implementation process may be carried out referring to the following content.

S1: acquiring logging data, seismic stack migration data and seismic pre-stack gather data of a certain target area.

In this embodiment, the selected logging well may specifically be well A. Correspondingly, the acquired relevant logging data and seismic stack migration data can be seen by referring to the playback schematic diagram of the well A logging curve obtained in one scenario example shown in FIG. 3. Specifically, the first shaft in the figure is geological stratification, the second shaft (CAL) is a lithology curve shaft of gamma energy spectrum, photoelectric absorption index and etc., and the third shaft (MD) is the measurement depth; the fourth shaft (RES) is an electrical curve of deep and shallow resistivity and etc.; the fifth shaft (XRD) is the total rock analysis result profile, the sixth shaft (FRAC) is the StatMin optimization calculation lithologic component profile, the seventh shaft (VCL) is the shaly content curve (among the 7th-13th shafts, the solid lines are curves of calculation and the

round point is the core analysis result); the eighth shaft (QUA) is the quartz content curve; the ninth shaft (CAR) is the carbonate content curve; the tenth shaft (PYR) is the pyrite content curve; the 11th shaft (TOC) is the TOC content curve; the 12th shaft (POR) is the porosity curve; the 13th shaft (SW) is the water saturation curve; and the last shaft (LITH) is the lithofacies result of division, in which "shale" denotes mud rocks, also called plastic shale, "sweet spot" denotes a shale gas reservoir, also known as brittle shale, i.e., a sweet spot, "limestone" denotes limestone, "shaly limestone" denotes argillaceous limestone. From detailed analysis of the data in FIG. 3, it can be seen that the thin interlayers in the area where the logging well is distributed at the following locations: 3197.65-3198.73m, 3207.25-3208.77m, 3209.12-4310.6m, and the thin interlayer of the carbonate rock has typical characteristics such as relatively higher resistivity, higher density and higher impedance, compared with the shale section. From the data in the schematic diagram of seismic stack migration data across well A and composite records acquired in one scenario example shown in FIG. 4, it can be seen that, the seismic data (i.e., seismic profile) for the area where Well A is located, due to the relatively low overall wave impedance of the shale section (showing the upper and lower surrounding rocks are all high impedance limestone), thus the reflection on the seismic profile is a valley-peak characteristic of strong energy, while the thin interlayer cannot be directly recognized and determined on the seismic profile due to its relatively thin thickness. With reference to the schematic diagram of a research area multi-well wavelet acquired in one scenario example shown in FIG. 5, since the thickness of the thin interlayer in the area is much lower than 1/4 wavelength (1/4.6 wavelength) of the seismic resolution, it can be seen from the wavelet extracted by drilling in the entire area (where the main frequency of the wavelet is about 21Hz, the bandwidth is 5-38Hz, and the phase is close to zero), the velocity of the target section is 5100m, the 1/4 wavelength corresponding to 38Hz is 33.6m, 1/8 wavelength is 16.8m, the thickness of the thin interlayer is 0.5-1.5m, and the accumulative thickness of the thin interlayers in logging is < 8.5m. Therefore, it can be judged that the conventional reservoir prediction means, that is, the existing methods, cannot effectively predict the thin interlayers that are relatively thin as described above.

In this embodiment, further, a comparison test may be performed by adopting the conventional means, that is, the existing methods. Specifically, with reference to the schematic diagram of a sectional view (top) and a plan view (bottom) of inversion obtained from geostatistics applying conventional logging constraints in one scenario example as shown in FIG. 6, it can be seen that, for prediction of the conventional thin layers (e.g., 1/16 wavelength < thickness < 1/8 wavelength), certain determination effect can be achieved relying solely on

logging constraint inversion (i.e., inversion is performed relying solely on the logging data as a constraint), but there is an insurmountable problem: because of the influence of variation, the inversion result will have a buphthalmia circle phenomenon, the reliability of prediction of the inversion result is reduced.

S2: determining a high-frequency three-dimensional lithologic probability volume of a thin interlayer based on the logging data, the core testing analysis data and the seismic stack migration data.

In this embodiment, considering that the pre-stack geostatistical inversion has the characteristics of high resolution, the information such as logging, petrophysics, sedimentary characteristics and the like can be well fused to obtain a plurality of elastic parameters such as a P-wave impedance, the ratio of compressional wave velocity to shear wave velocity, a density and etc. Therefore, consideration may be given that a high-resolution three-dimensional probability volume (i.e. the high-frequency three-dimensional lithologic probability volume of the thin interlayer) can be used as an input to carry out the pre-stack geostatistical inversion, and the inversion result can better recognize complex lithology, and better solve deficiency of conventional one-dimensional and two-dimensional constraints, so as to achieve the effects of improving longitudinal resolution, better matching the well point data, being not easily affected by the variation parameters, having no buphthalmia at the well points, and the like.

In this embodiment, in order to determine the aforementioned three-dimensional probability volume, in specific implementation, the following steps may be performed:

S2-1: performing logging evaluation and petrophysical analysis on the aforementioned logging data.

This step mainly carries out logging consistency processing, logging curve correction, multi-well logging evaluation and etc., and obtains logging curves with good consistency law and logging evaluation results reflecting sedimentary characteristics (that is, interlayer probability response characteristics of the logging and reservoir probability response characteristics of the logging), which specifically may include: critical parameters such as shale content, calcareous content (i.e. limestone content), porosity, brittleness, and etc., and may further establish a first high-frequency probability volume with respect to the distribution of thin interlayers.

S2-2: performing gather processing and AVA wavelet extraction.

This step mainly carries out gather processing, angle calculation, resolution shift distance superposition and the like for original CRP gather, wherein the gather processing may

specifically include de-noising process, residual static correction, multiple wave attenuation, and etc.; on the basis of this, AVA wavelet extraction is performed (corresponding to the determination of the partial migration stack data volume) by combining the logging curve to lay a foundation for the subsequent pre-stack inversion.

S2-3: performing three-dimensional seismic inversion and attribute analysis (corresponding to determining a second high-frequency probability volume with respect to distribution of thin interlayers based on the logging data and the seismic stack migration data).

This step can obtain an initial model consistent with the distribution of limestone (i.e. calcareous distribution), that is, the second high-frequency probability volume with respect to the distribution of thin interlayers, mainly by carrying out conventional post-stack wave impedance inversion and attribute analysis.

S2-4: establishing a three-dimensional volume model for the distribution probability of thin interlayers (corresponding to determining a high-frequency three-dimensional lithologic probability volume of the thin interlayer based on the first high-frequency probability volume and the second high-frequency probability volume).

This step mainly aims to establish an initial three-dimensional probability model for the thin interlayer of limestone (i.e., the high-frequency three-dimensional lithologic probability volume of the thin interlayer), specifically, three-dimensional volume modeling can be carried out by using multi-well logging evaluation results, combining with the conventional seismic inversion results and attributes, using the global Kriging method, to obtain a three-dimensional probability model of thin interlayer of limestone with good consistency with well points and conforming to spatial changes. Such result data are relatively reasonable, and can maximize the fusion of logging, geology and other multiple information, and thus having characteristics of a high longitudinal resolution and a reasonable spatial law. Specifically, reference may be made to FIG. 7, which is a schematic cross-sectional view of a three-dimensional probability volume obtained by applying the method and the apparatus of determining thin interlayers according to the embodiments of the present application in one scenario example.

S3: using the high-frequency three-dimensional lithologic probability volume of the thin interlayer as a constraint, determining the thin interlayer in the target area by the pre-stack geostatistical inversion.

This step is different from the previous conventional pre-stack geostatistical inversion in that a three-dimensional probability volume of limestone interlayers is introduced (i.e., a high-frequency three-dimensional lithologic probability volume of thin interlayers), and in specific implementation, this probability volume may serve as data similar to the

"sand-to-ground ratio" attribute, as a high-resolution soft constraint, and thus as an input to geostatistics, and by means of pre-stack geostatistical inversion, the results of pre-stack geostatistical inversion with a high longitudinal resolution and consistent with spatial sedimentary law can be obtained. The inversion results may specifically include parameters such as a P-wave impedance, the ratio of compressional wave velocity to shear wave velocity, a density and etc. Then interpretation is carried out with the understanding of petrophysics, a high-resolution limestone interlayer can be obtained, and dessert distribution, brittleness and other parameters can further be determined.

The results determined by applying the method and the apparatus of determining thin interlayers provided by the present application are specifically compared with the results obtained by applying the conventional methods for analysis. Reference may be made to FIG. 8 which is a schematic diagram of an inversion effect map using conventional geostatistics in one scenario example and to FIG. 9 which is a schematic diagram of a pre-stack geostatistical inversion of the high-frequency three-dimensional lithologic probability volume constraints obtained using the method and the apparatus of determining thin interlayers according to the embodiments of the present application in one scenario example, it can be seen that in the example shown in FIG. 9, the logging information and the seismic information are well fused, the result resolution is high, the spatial law is relatively reasonable, and the limestone interlayer (that is, the thin interlayer) can be well delineated. Reference may be made to FIG. 10 which is a schematic cross-sectional view showing results of probability inversion of a final limestone interlayer across a well over the whole area obtained by applying the method and the apparatus of determining thin interlayers according to the embodiments of the present application in one scenario example, it can be seen that the result of inversion is in good agreement with that of drilling, which can well delineate the distribution of the limestone interlayer in the shale section and achieve the organic unity of the logging information and the seismic information.

In general, application of the method and the apparatus of determining thin interlayers provided by the present application can better solve the problem of prediction of thin interlayers during shale gas exploration, and has characteristics of strong operability and applicability, and can achieve a particularly obvious effect especially for medium thin interlayers in similar marine ultrathin mud sand-covered area.

In the aforementioned scenario examples, the method and the apparatus of determining thin interlayers provided by the embodiments of the present application are verified, the high-frequency three-dimensional lithologic probability volume of the thin interlayer having a

high resolution and a good characterization effect and being capable of reflecting the longitudinal change trend is determined by comprehensively utilizing the logging data and the seismic data; then the specific thin interlayer is determined by the pre-stack geostatistical inversion, using the above described high-frequency three-dimensional lithologic probability volume of the thin interlayer as a constraint, so as to indeed solve the technical problems of the existing methods that determination of thin interlayers has a large error and the resolution is low, to achieve the technical effect of not only reflecting longitudinal change trend characteristics but also reflecting horizontal change trend characteristics, thereby being possible to determine thin interlayers more precisely.

Although mentioning different embodiments, the present application is not limited to the industry standards, the situations described in the embodiments or the like. Some industry standards, customized implementation solutions, or implementation solutions slightly amended based on those described in the embodiments can also achieve the same, equivalent or similar implementation effects of the above embodiments or implementation effects predictable after modification. The embodiments applying the manners of data acquisition, processing, output, judgement, etc. after amendment or modification still fall within the range of the optional implementation solutions of the present application.

Although the present application provides the method operation steps as described in the embodiments or the flowcharts, more or less operation steps may be included based on the conventional or non-creative means. The order of the steps listed in the embodiments is merely one of various execution orders of the steps, rather than a unique execution order. At an actual device or client product, the steps may be performed in sequence or in parallel according to the methods illustrated in the embodiments or drawings (e.g., by a parallel processor or under a multi-threaded processing environment and even a distributed data processing environment). The term “comprise”, “include” or any other variant intends to cover the non-exclusive inclusions, so that a process, a method, a commodity or a device comprising a series of elements comprise not only those elements, but also other elements not explicitly listed, or further comprise inherent elements of such process, method, commodity or device. In a case where there is no further limitation, it does not exclude other identical elements existing in the process, method, commodity or device comprising the elements.

Any apparatus, module or the like set forth in the embodiments specifically may be implemented by a computer chip or an entity, or by a product having a certain function. For the convenience of description, when an apparatus is to be described, it is divided into various

modules based on its functions and described respectively. Without doubt, when the present application is implemented, the functions of the various modules may be realized in the same one or more software and/or hardware, or a module that realizes a function may be implemented by a combination of a plurality of submodules. The apparatus embodiments described above are merely illustrative. For instance, the division of the module is only a logical function division, and there may be other division manners during actual implementation, e.g., a plurality of modules or components may be combined or integrated into another system, or some features may be omitted or not implemented.

As also known to those skilled in the art, in addition to implementing the controller merely with the computer readable program codes, it is completely possible to logically program the methodical steps to enable the controller to realize the same function in the form such as a logic gate, a switch, an application-specific integrated circuit, a programmable logic controller, or an embedded microcontroller. Thus, the controller may be considered as a hardware component, while means included therein for realizing various functions may also be regarded as structures within the hardware component. Or, the means for realizing various functions even may be regarded as either software modules that can implement the method or structures within the hardware component.

The present disclosure may be described in the general context of computer executable instructions executed by the computer, e.g., the program module. In general, the program module includes routine, program, object, component, data structure, etc. executing a particular task or realizing a particular abstract data type. The present disclosure may also be put into practice in the distributed computing environments where tasks are executed by remote processing devices connected through a communication network. In the distributed computing environments, the program modules may be located in the local and remote computer storage medium including the storage device.

As can be seen from the descriptions of the above embodiments, those skilled in the art can clearly understand that the present disclosure can be implemented by means of software plus a necessary universal hardware platform. Based on this understanding, the essence of the technical solution of the present disclosure or the part making a contribution to the prior art can be embodied in the form of a computer software product, which may be stored in a storage medium, such as a ROM/RAM, a magnetic disk, an optical disk, etc., and include several instructions to enable a computer device (a personal computer, a server, a network device, etc.) to carry out the embodiments of the present disclosure, or methods described in some parts of the embodiments.

The embodiments herein are all described in a progressive manner, and the same or similar portions of the embodiments can refer to each other. Each embodiment lays an emphasis on its distinctions from other embodiments. The present application may be used in a variety of general or dedicated computer system environments or configurations, such as a personal computer, a server computer, a handheld or portable device, a tablet device, a multiprocessor system, a microprocessor-based system, a set-top box, a programmable electronic device, a network PC, a small-scale computer, a large-scale computer, a distributed computing environment including any of the above systems or devices, and the like.

Although the present application is described through the embodiments, those skilled in the art will know that that there are many modifications and changes of the present application without deviating from the spirit of the present application, and it is intended that the appended implementations include those modifications and changes without deviating from the spirit of the present application.

Claims

1. A method of determining thin interlayers, characterized in comprising:

acquiring logging data, core testing analysis data, seismic pre-stack gather data, seismic stack migration data and seismic interpretation horizon data of a target area;

determining a high-frequency three-dimensional lithologic probability volume of a thin interlayer based on the logging data, the core testing analysis data, the seismic stack migration data and seismic interpretation horizon data, wherein the high-frequency three-dimensional lithologic probability volume serves as an input to pre-stack geostatistical inversion and is a high-frequency lithology probability volume established by utilizing logging data and seismic data, wherein a frequency band of the high-frequency three-dimensional lithologic probability volume exceeds the dominant bandwidth range of the seismic data;

determining the thin interlayer in the target area by the pre-stack geostatistical inversion according to the seismic pre-stack gather data, using the high-frequency three-dimensional lithologic probability volume of the thin interlayer as a constraint.

2. The method according to claim 1, characterized in that, the determining a high-frequency three-dimensional lithologic probability volume of a thin interlayer based on the logging data, the core testing analysis data, the seismic stack migration data and seismic interpretation horizon data, comprises:

determining a first high-frequency probability volume with respect to distribution of thin interlayers based on the logging data, the core testing analysis data, and the seismic interpretation horizon data;

determining a second high-frequency probability volume with respect to distribution of thin interlayers based on the logging data, the seismic stack migration data, and the seismic interpretation horizon data;

determining a high-frequency three-dimensional lithologic probability volume of the thin interlayer based on the first high-frequency probability volume and the second high-frequency probability volume.

3. The method according to claim 2, characterized in that, the determining a first high-frequency probability volume with respect to distribution of thin interlayers based on the logging data, the core testing analysis data, and the seismic interpretation horizon data, comprises:

determining a logging response characteristic of the interlayer through logging evaluation according to the logging data;

obtaining petrophysical analysis result data through petrophysical analysis according to

the logging data;

establishing a probability curve of distribution of on-well interlayers according to the petrophysical analysis result data, the logging response characteristics, and the core testing analysis data;

obtaining the first high-frequency probability volume with respect to distribution of thin interlayers by inter-well interpolation of the probability curve of distribution of on-well interlayers within the target horizon, according to the logging response characteristic of the interlayer.

4. The method according to claim 3, characterized in that, the determining a second high-frequency probability volume with respect to distribution of thin interlayers based on the logging data, the seismic stack migration data, and the seismic interpretation horizon data, comprises:

performing a seismic waveform difference simulation on the seismic stack migration data within a target horizon by utilizing the probability curve of distribution of on-well interlayers, to obtain the second high-frequency probability volume with respect to distribution of thin interlayers.

5. The method according to claim 2, characterized in that, the determining a high-frequency three-dimensional lithologic probability volume of the thin interlayer based on the first high-frequency probability volume and the second high-frequency probability volume, comprises:

fusing the first high-frequency probability volume and the second high-frequency probability volume through a global Kriging method in a frequency domain to obtain a high-frequency three-dimensional lithologic probability volume of the thin interlayer.

6. The method according to claim 1, characterized in that, the determining the thin interlayer in the target area by the pre-stack geostatistical inversion according to the seismic pre-stack gather data, using the high-frequency three-dimensional lithologic probability volume of the thin interlayer as a constraint, comprises:

performing gather processing on the seismic pre-stack gather data to obtain partial stack migration data and full stack migration data;

determining the thin interlayer in the target area by the pre-stack geostatistical inversion, based on the partial stack migration data and the full stack migration data, using the high-frequency three-dimensional lithologic probability volume of the thin interlayer as a constraint.

7. The method according to claim 6, characterized in that, the gather processing

comprises at least one of:

de-noising process, residual static correction process, multiple wave attenuation process, gather flattening process, gather removing process, and partial stack process.

8. The method according to claim 6, characterized in that, the using the high-frequency three-dimensional lithologic probability volume of the thin interlayer as a constraint, determining the thin interlayer in the target area by the pre-stack geostatistical inversion, based on the partial stack migration data and the full stack migration data, comprises:

using the high-frequency three-dimensional lithologic probability volume of the thin interlayer as a constraint, performing pre-stack geostatistical inversion on the partial stack migration data and the full stack migration data to determine an inversion result, wherein the inversion result comprises a P-wave impedance data volume, the ratio of compressional wave velocity to shear wave velocity data volume, and a density data volume;

determining the thin interlayer in the target area based on the inversion result.

9. The method according to claim 1, characterized in that, after determining the thin interlayer in the target area, the method further comprises:

directing shale gas exploration of the target area according to the thin interlayer.

10. The method according to claim 1, characterized in that, the frequency band is 60-500 Hz.

11. An apparatus of determining thin interlayers, characterized in comprising:

an acquisition module for acquiring logging data, core testing analysis data, seismic pre-stack gather data, seismic stack migration data and seismic interpretation horizon data of a target area;

a first determination module for determining a high-frequency three-dimensional lithologic probability volume of a thin interlayer based on the logging data, the core testing analysis data, the seismic stack migration data and seismic interpretation horizon data, wherein the high-frequency three-dimensional lithologic probability volume serves as an input to pre-stack geostatistical inversion and is a high-frequency lithology probability volume established by utilizing logging data and seismic data, wherein a frequency band of the high-frequency three-dimensional lithologic probability volume exceeds the dominant bandwidth range of the seismic data;

a second determination module for using the high-frequency three-dimensional lithologic probability volume of the thin interlayer as a constraint, determining the thin interlayer in the target area by the pre-stack geostatistical inversion according to the seismic pre-stack gather data.

12. The apparatus according to claim 11, characterized in that, the first determination module comprises:

a first determination unit for determining a first high-frequency probability volume with respect to distribution of thin interlayers based on the logging data, the core testing analysis data, and the seismic interpretation horizon data;

a second determination unit for determining a second high-frequency probability volume with respect to distribution of thin interlayers based on the logging data, the seismic stack migration data, and the seismic interpretation horizon data;

a third determination unit for determining a high-frequency three-dimensional lithologic probability volume of the thin interlayer based on the first high-frequency probability volume and the second high-frequency probability volume.

13. The apparatus according to claim 11, characterized in that, the second determination module comprises:

a processing unit for performing gather processing on the seismic pre-stack gather data to obtain partial stack migration data and full stack migration data;

a fourth determination unit for using the high-frequency three-dimensional lithologic probability volume of the thin interlayer as a constraint, determining the thin interlayer in the target area by the pre-stack geostatistical inversion, based on the partial stack migration data and the full stack migration data.