Multi-parameter inversion through offset dependent elastic FWI

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ABSTRACT

Method for multi-parameter inversion using elastic inversion. This method decomposes data into offset/angle groups and performs inversion on them in sequential order. This method can significantly speed up convergence of the iterative inversion process, and is therefore most advantageous when used for full waveform inversion (FWI). The present inventive approach draws upon relationships between reflection energy and reflection angle, or equivalently, offset dependence in elastic FWI. The invention uses recognition that the amplitudes of small angle (near offset) reflections are largely determined by acoustic impedance alone (**1**), independent for the most part of Vp/Vs. Large angle (middle and far offset) reflections are affected by Ip, Vp/Vs (**2**) and other earth parameters such as density (**3**) and anisotropy. Therefore, the present inventive method decomposes data into angle or offset groups in performing multi-parameter FWI to reduce crosstalk between the different model parameters being determined in the inversion.

IMAGES (7)

Patent Drawing   Patent Drawing   Patent Drawing   Patent Drawing   Patent Drawing   Patent Drawing   Patent Drawing

DESCRIPTION

CROSS-REFERENCE TO RELATED APPLICATION

This application claims the benefit of U.S. Provisional Patent Application 61/827,474, filed May 24, 2013, entitled "Multi-Parameter Inversion through Offset Dependent Elastic FWI," the entirety of which is incorporated by reference herein.

FIELD OF THE INVENTION

The invention relates generally to the field of geophysical prospecting including prospecting for hydrocarbons and, more particularly, to seismic data processing. Specifically, the invention is a method for elastic full wavefield inversion ("FWI") of seismic data to obtain a subsurface model of multiple physical parameters.

BACKGROUND OF THE INVENTION

An inversion process in geophysics data processing usually, and in the case of this document as well, refers to the process of transforming seismic reflection data into a quantitative rock-property description of a reservoir in the form of a subsurface earth model. Such a model needs three parameters, which are density (ρ), P-wave velocity (V_P) and S-wave velocity (V_S) to describe it, if the model is assumed to be isotropic. Additional parameters are needed in a more general subsurface model that includes anisotropy and attenuation. There are many techniques used in inversion at seismic resolution, such as post-stack or pre-stack AVO inversion and Full-Waveform Inversion (FWI).

It is well known that PP reflection (P-wave down/P-wave up) at normal incident angle is largely determined by the acoustic impedance $I_p=\rho V_p$. In order to estimate I_p from seismic data, it is usually sufficient to consider only P-wave

CLAIMS (11)

The invention claimed is:

1. A computer-implemented method for full wavefield inversion of seismic data to infer subsurface physical property parameters including P-wave (pressure wave) velocity, S-wave (shear wave) velocity, and density, comprising:

extracting only PP mode (P-wave down/P-wave up) from the seismic data, and inverting, with a full wavefield inversion algorithm, the PP mode data sequentially in two or more different offset ranges, each offset range full wavefield inversion determining at least one physical property parameter, wherein in a second and subsequent full wavefield inversions, parameters determined in a previous inversion are held fixed, and further wherein all full wavefield inversions are performed using a computer; and

generating, with a computer, a subsurface physical property model that includes the P-wave velocity, S-wave velocity, and the density from the full wavefield inversion algorithm, which transforms the seismic data into the subsurface physical property model, wherein the subsurface physical property model is a quantitative rock-property description of a hydrocarbon reservoir, and using the subsurface physical property model for geophysical prospecting.

2. The method of claim 1, wherein a near offset range is sequentially first to be inverted, and said first full wavefield inversion infers P-wave acoustic impedance Ip, using a computer programmed with an acoustic full wavefield inversion algorithm.

3. The method of claim 2, wherein a mid-offset range is sequentially second to be inverted, and said second full wavefield inversion infers

good indicator of reservoir rocks and types. It is know that fluid types can be better retrieved from elastic parameters such as V_P/V_S. As a result, multi-parameter inversion for both acoustic and elastic parameters has become desirable, perhaps almost necessary, in reservoir characterization.

Multi-parameter inversion through elastic FWI has a unique role in delineating reservoir characters as it is based on accurate modeling of elastic wave propagation. Elastic FWI is a highly expensive process for two main reasons. First, finite difference modeling becomes far more expensive than under the acoustic (P-wave only) assumption due to denser computational grids needed for computer simulation of shear wave propagation. Second, multi-parameter inversion requires many more iterations than acoustic FWI to achieve convergence and reduce crosstalk between different parameters. In reservoir characterization, the most important parameters to describe rock properties are acoustic impedance I_p and the velocity ratio V_p/V_S. Therefore, there is a need for an FWI method than can robustly invert for I_p and V_p/V_S in a small number of iterations (preferably ~10) to make it practical in business applications such as reservoir characterization and velocity model building.

There are a wide variety of methods to estimate rock properties from seismic data. The procedure proposed by Hampson et al. (2005) represents a typical workflow in pre-stack AVO inversion. In their workflow, I_P, I_S and density are estimated simultaneously based on AVO in angle gathers and the Aki-Richards equations (Aki and Richards, 2002). Their approach is based on linearized approximation for reflectivity instead of the iterative process of simulating elastic waves and matching waveforms. Computational cost is therefore much cheaper in pre-stack inversion due to the linearized approximation. In contrast, elastic FWI, although a much more expensive process, has the potential to generate superior results.

SUMMARY OF THE INVENTION

The present invention is a robust and efficient computer-implemented method for multi-parameter inversion using elastic FWI. This method decomposes data into offset or angle groups and performs elastic FWI on them in sequential order. This method can significantly speed up convergence, by a factor of approximately 10 in some examples, compared to elastic FWI carried out without the improvements of the present invention. The present inventive approach draws upon the relationship between reflection energy and reflection angle, or equivalently, offset dependence in elastic FWI. From the classic AVO theory by Aki and Richards (1980), it is known that the amplitudes of small angle (near offset) reflections are largely determined by acoustic impedance alone, independent for the most part of Vp/Vs. Large angle (middle and far offset) reflections are affected by Ip, Vp/Vs, and other earth parameters such as density and anisotropy. Therefore, the present inventive method decomposes data into angle/offset groups in performing multi-parameter FWI to reduce crosstalk between different model parameters, i.e. between the inversion unknowns. For purposes of this disclosure, including the appended claims, it shall be understood that decomposing the data into angle groups is equivalent to decomposing the data into offset groups, and the one term shall be understood to include the other.

In one embodiment, the invention is a computer-implemented method for inversion of seismic data to infer subsurface physical property parameters including P-wave velocity, S-wave velocity, and density, comprising extracting only PP mode from the seismic data, and inverting the PP mode data sequentially in two or more different offset ranges, each offset range inversion determining at least one physical property parameter, wherein in a second and subsequent inversions, parameters determined in a previous inversion are held fixed.

In another embodiment, the invention is a method for inversion of seismic data to infer at least P-wave velocity, S-wave velocity, and density, comprising: (a) taking only PP-mode data from the seismic data, and dividing the seismic data into a

S-wave velocity V_S, with I_P fixed at its value from the first full wavefield inversion, said second full wavefield inversion using an elastic inversion algorithm.

4. The method of claim 3, wherein a far-offset range is sequentially third to be inverted and said third full wavefield inversion infers density or V_P, using an elastic full wavefield inversion algorithm, with I_P fixed at its value from the first full wavefield inversion and V_P/V_S fixed at a value determined from the second full wavefield inversion.

5. The method of claim 4, wherein V_P and Vs are computed from I_P and I_S using definition of acoustic impedance, and using density as inferred in the third full wavefield inversion.

6. The method of claim 4, wherein V_P is inferred in the third full wavefield inversion, and density is computed from the relationship $I_P=\rho V_P$ and I_P is as determined in the first full wavefield inversion.

7. The method of claim 4, wherein one or both of the relationships $I_P=\rho V_P$ and $I_P=\rho V_S$ are used in performing the method.

8. The method of claim 4, further comprising repeating the sequential full wavefield inversions at least one time to update the inferred physical property parameters.

9. A computer-implemented method for inversion of seismic data to infer at least P-wave (pressure wave) velocity, S-wave (shear wave) velocity, and density, comprising:

(a) taking only PP-mode (P-wave down/P-wave up) data from the seismic data, and dividing the seismic data into a near-offset range, a mid-offset range, and a far offset range, which ranges may or may not overlap;

(b) inverting the near offset range for P-wave acoustic impedance IP, using a computer programmed with an acoustic full wavefield inversion algorithm;

(c) inverting the mid-offset range for S-wave acoustic impedance Is, or for P-wave velocity V_P divided by S-wave velocity V_S, with I_P fixed at its value from (b), using an elastic full wavefield inversion algorithm;

(d) inverting the far-offset range for density, using an elastic full wavefield inversion algorithm, with I_P fixed at its value from (b) and V_P/V_S fixed at a value determined from the value of I_S from (c);

(e) computing V_P and V_S from I_P and I_S using definition of acoustic impedance and density as determined in (d); and

(f) generating, with a computer, a subsurface physical property model that includes the P-wave velocity, S-wave velocity, and the density, wherein the steps (b), (c), and (d) transform the seismic data into the subsurface physical property model, wherein the subsurface physical property model is a quantitative rock-property description of a hydrocarbon reservoir, and using the subsurface physical property model for geophysical prospecting.

10. The method of claim 1, wherein at least some of the two or more different offset ranges overlap.

11. The method of claim 1, wherein at least some of the two or more different offset ranges do not overlap.

offset range for P-wave acoustic impedance I_P, using a computer programmed with an acoustic inversion algorithm; (c) inverting the mid-offset range for S-wave acoustic impedance I_S, or for P-wave velocity V_P divided by S-wave velocity V_S, with I_P fixed at its value from (b), using an elastic inversion algorithm; (d) inverting the far-offset range for density, using an elastic inversion algorithm, with I_p fixed at its value from (b) and V_P/V_S fixed at a value determined from the value of I_S from (c); and (e) computing V_P and V_S from I_P and I_S using definition of acoustic impedance and density as determined in (d).

In a typical case, the near-offset range might be <500 m with the far-offset range being >2 km, and the mid-offset range being in between.

BRIEF DESCRIPTION OF THE DRAWINGS

The advantages of the present invention are better understood by referring to the following detailed description and the attached drawings, in which:

FIG. 1 is a flowchart showing basic steps in one embodiment of the seismic processing method of the present invention;

FIG. 2 shows the true Vp, Vs and density profiles used to generate a synthetic gather, and one of the shot gathers;

FIG. 3 shows inversion of I_P using near offset data and data misfit, compared with true I_P and synthetic data;

FIG. 4 shows I_p alone without knowledge of V_p/V_s is not able to explain middle offset data;

FIG. 5 shows inversion of V_P/V_S with I_p fixed from FIG. 2 explains seismic data up to the middle offsets; and

FIG. 6 shows the results of inversion of density from far offset data, with I_P and V_P/V_S fixed from FIG. 2 and FIG. 4.

Many of the drawings are color originals converted to gray scale because of patent law restrictions on the use of color.

The invention will be described in connection with example embodiments. However, to the extent that the following detailed description is specific to a particular embodiment or a particular use of the invention, this is intended to be illustrative only, and is not to be construed as limiting the scope of the invention. On the contrary, it is intended to cover all alternatives, modifications and equivalents that may be included within the scope of the invention, as defined by the appended claims.

DETAILED DESCRIPTION OF EXAMPLE EMBODIMENTS

In the elastic FWI method presented by ("SSB" for short) Sears, Singh and Barton (2008), a three-stage workflow was proposed to estimate Vp and Vs from P-wave and S-wave seismic data: stage one, inversion for short and intermediate scale Vp using normal-incidence and wide-angle P-wave data; stage two, inversion for intermediate Vs using wide-angle P-wave data; and stage three, inversion for short-scale Vs using PS-wave data. Short and intermediate scale are terms used in the SSB paper. General speaking, short-scale refers to spatial scales that can be inferred directly from high frequency reflection energy in seismic data, and large-scale refers to spatial scales whose reflected frequencies are below typical seismic sources (e.g., 4-6 Hz in marine acquisition). Therefore, the large-scale is typically inferred from migration velocity analysis. The gap between large-scale and short-scale is usually called intermediate-scale.

While the SSB method may at first appear similar to the 3-step inventive method that is disclosed herein, there are important features that distinguish them. First, the SSB method uses different wave modes through the 3 stages. The present inventive method uses the same wave mode (PP-wave) but different reflection angle/offset through the 3 steps. It is well known that PP-wave data represent most of the recorded energy in a typical seismic survey, and therefore most of the value in marine streamer acquisition. Second, the SSB method does not separate normal-incidence and wide-angle P-wave data in stage 1 and uses them simultaneously. The present inventive method uses only small angle reflection data in step 1, which is the critical step of speeding up convergence.

A synthetic example is used to demonstrate that this method is very robust and effective in retrieving Ip and Vp/Vs. The total number of iterations needed to get Ip and Vp/Vs is ˜10. Retrieving density information in step 3 (see the FIG. 1 flow chart) may require an additional 10-15 iterations in the synthetic example. Tests on field data show that accurate and robust estimate of I_p and V_P/V_s can be obtained within ˜10 iterations as well. However, in the field data case, the reliability of the density inversion is strongly subject to the accuracy of the velocity model, including anisotropy, and data quality at far-offsets.

The synthetic example follows the embodiment of the present inventive method illustrated in the flow chart of FIG. 1. Synthetic (computer simulated) data are used in this test example to demonstrate the invention. The data set is generated by isotropic elastic finite difference modeling on a layered (1D) earth model shown in FIG. 2, where V_P, V_S and density are plotted vs. depth in the subsurface. The units for velocity and density are m/s and kg/m³. A common-shot gather of the synthetic "measured" data is also shown at **8** in FIG. 2. Time in seconds is plotted on the vertical axis, and offset in meters is plotted on the horizontal axis. The maximum depth of the earth model is 2.3 km and the maximum offset available is 5

data display, where color is used to represent the magnitude of seismic amplitudes. The same is true of the comparisons of simulated to measured data, and the misfits, shown in FIGS. 3-6.

Step 1: Inversion of Ip from Near Offset Data.

First, acoustic FWI is performed using near offset PP data (offset <500 m) to get an estimate of I_P, which is plotted in FIG. 3. As explained above, PP-wave data at small reflection angles (equivalently, small offsets in this example) are determined by acoustic impedance I_p. Elastic parameters have very little effect on small angle PP reflection data. Initial V_P and density models are needed to perform acoustic FWI. The initial V_P model can be derived from traditional migration velocity analysis, and for this synthetic test, a smoothed version of the "true" V_P profile (used to forward model the synthetic data) in FIG. 2 was used. The initial density model can be derived from an empirical relationship between density and V_P. For simplicity, a constant density (1,000 kg/m^3) model was used to start with. From the mathematical definition

$$I_p = \rho V_p, \qquad (1)$$

it is clear that inverted I_P with known density ρ can be directly translated to V_p after dividing I_P by density ρ. The results at iteration 5 of I_P and V_P are shown in both time and depth domain in FIG. 3, where the dark lines are the inverted model and the lighter shaded lines are the synthetic model. The inverted unknown is I_p in this case. An estimate of V_p may then be obtained by dividing inverted I_p by ρ according to equation (1). In FIG. 3, the inverted models are overlaid with the true synthetic models for comparison. All inversions are performed in depth domain (meters); the results are shown at **11** and **12**. For comparison in certain frequency range, inversion results are converted to time (seconds) by depth-to-time conversion using the smoothed version of true V_p in FIG. 2. The comparisons in time domain (**9** and **10**) are limited within 5-40 Hz after applying band-pass filter. From **9** and **11**, it can be seen that the inverted Ip matches synthetic model very well. Since V_p was derived from the inverted I_p based on an assumed constant ρ according to Eqn. (1), a good match between derived V_p and the true V_p is not expected (no updated estimation of ρ has been performed yet). Thus, the initial density model (constant) is very different from the synthetic density model (**7** in FIG. 2), and this difference is reflected in V_P due to equation (1). This is particularly indicated in **10** by the mismatch in time domain at about 1.75 s and a similar mismatch in depth domain (**12**) at about 1800 m. It can be seen in **9** and **11** that the mismatch for I_P is much less at that particular time and depth.

Data misfit **15**, i.e. the difference between measured data **13** (from synthetic models) and simulated data **14** (from inverted I_p, constant density and derived V_p according to (1)), is shown in FIG. 3. The difference is actually negligible. Data misfit is a very important criterion for convergence check during inversion of field (actual) data because in a field data application, a 'true model' is seldom known. Generally speaking, when other conditions are similar, better data misfit usually, but not always, indicates higher confidence in the inversion product. The negligible amount of misfit indicates that near offset data can be well explained by Ip alone.

Step 2: Inversion of I_S or V_P/V_S from Middle Offset (<2 km) Data with I_P Fixed from the Previous Step.

The following are known, simple relationships:

$$I_S = \rho V_S \qquad (2)$$

$$I_S = \frac{V_S}{V_p} I_p, \qquad (3)$$

where Eqn. (3) results directly from Eqs. (1) and (2). In this step 2, the inversion needs to be elastic and the inversion unknown was V_p/V_s. Since I_p is fixed from the previous step, inverting for V_p/V_s is equivalent to inverting for I_s in this step according to (3). Alternatively, the inversion unknown could be I_S. FIG. 4 shows difference between initial Vs model (dark line, constant) and synthetic model (lighter shaded line) in **18**, and the ratio Vp/Vs is shown in **19**. With this initial Vs model, and Vp (shown in **17**) and density (constant) from step 1, a large data misfit may be observed in panel **22** when extending the offset to 2 km, as indicated in FIG. 4. This is because I_p alone is not adequate to explain middle reflection angle (offset) data. A good estimate for the second parameter, which is V_p/V_s is needed to explain middle offset data. However, the data misfit at near offset is still as small as in FIG. 3 (**15**) because I_P is fixed (**16**, **9**) from step 1.

Following the same layout as FIG. 3 used in displaying step 1 inversion results, FIG. 5 shows the inverted V_P/V_S (dark line, **26**) after 5 iterations, overlaid with the synthetic model (lighter shaded line, **26**). The inverted model matches the synthetic model very well. As indicated at panel **29**, the data misfit at the middle offset range (500 m to 2 km, scale not shown in the drawing) is greatly reduced by having the benefit of the inverted V_P/V_S model. In the step 2 inversion, I_P (**23**) and V_P (**24**) are fixed from step 1. From equation (3), an accurate I_s can be derived from accurate inversion results of I_p and V_p/V_s. But V_s from Eqn. (2) will not be as accurate if information on density is missing or inaccurate. This is indicted at time≈1.75 s in panel **25** in FIG. 5, where it can be seen that Vs derived from V_p/Vs does not match synthetic model to the same degree as V_p/V_s.

Step 3: Inversion of Density from Far Offset (Up to 5 km) Data with I_P and V_P/V_S Fixed from the Previous Two Steps.

The mathematical relations (1)-(3) indicate that any update of density with I_p and V_P/V_S being fixed results in an update to V₍ and V₍. Therefore, inversion of density with I₍ and V₍/V₍ fixed is equivalent to inversion of V₍. In step 3, all available

1 and 2. FIG. 6 shows inverted density (dark line, **33**) after 10 iterations, overlaid with the synthetic model (lighter shaded line, **33**), where the synthetic model is **7** in FIG. 2, converted to time domain. At the same time, step 3 results in an improved prediction of V_P (**31**, dark line) compared with that of FIG. 3 (**10**, dark line) due to the updated density profile **33**. Data misfit is mostly at far offsets (2 km to 5 km) as is shown at **36** in FIG. 3.

The foregoing description is directed to particular embodiments of the present invention for the purpose of illustrating it. It will be apparent, however, to one skilled in the art, that many modifications and variations to the embodiments described herein are possible. All such modifications and variations are intended to be within the scope of the present invention, as defined by the appended claims.

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CLASSIFICATIONS

International Classification	G01V1/28, G01V1/30
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