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/m^3. 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/V_s 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 V̲ ̲a̲n̲d̲ ̲V̲. ̲T̲h̲e̲r̲e̲f̲o̲r̲e̲,̲ ̲i̲n̲v̲e̲r̲s̲i̲o̲n̲ ̲o̲f̲ ̲d̲e̲n̲s̲i̲t̲y̲ ̲w̲i̲t̲h̲ ̲I̲ ̲a̲n̲d̲ ̲V̲ ̲/̲V̲ ̲f̲i̲x̲e̲d̲ ̲i̲s̲ ̲e̲q̲u̲i̲v̲a̲l̲e̲n̲t̲ ̲t̲o̲ ̲i̲n̲v̲e̲r̲s̲i̲o̲n̲ ̲o̲f̲ ̲V̲.̲ ̲I̲n̲ ̲s̲t̲e̲p̲ ̲3̲,̲ ̲a̲l̲l̲ ̲a̲v̲a̲i̲l̲a̲b̲l̲e̲

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.

REFERENCE

- Aki and Richards, *Quantitative Seismology, Theory and Methods*, chapter 5.20, W. H. Freeman & Co. (1980).
- Lazaratos, S., Chikichev, I. and Wang, K., 2011, Improving convergence rate of Full Wavefield Inversion (FWI) using spectral shaping, PCT patent application publication WO2012/134621.
- Hampson, Russell, and Bankhead, "Simultaneous inversion of pre-stack seismic data," 75th Annual International Meeting, SEG, Expanded Abstracts, 1633-1637 (2005).
- Sears, Singh and Barton, "Elastic full waveform inversion of multi-component OBC seismic data," *Geophysical Prospecting* 56, 843-862 (2008)

PATENT CITATIONS

Cited Patent	Filing date	Publication date	Applicant	Title
US3812457	Nov 17, 1969	May 21, 1974	Shell Oil Co	Seismic exploration method
US3864667	Sep 11, 1970	Feb 4, 1975	Continental Oil Co	Apparatus for surface wave parameter determination
US4159463	Oct 21, 1977	Jun 26, 1979	Daniel Silverman	Method of three dimensional seismic prospecting
US4168485	Jun 30, 1976	Sep 18, 1979	Continental Oil Company	Simultaneous use of pseudo-random control signals in vibrational exploration methods
US4545039	Sep 9, 1982	Oct 1, 1985	Western Geophysical Co. Of America	Methods for seismic exploration
US4562540	Nov 12, 1982	Dec 31, 1985	Schlumberger Technology Corporation	Diffraction tomography system and methods
US4575830	Oct 15, 1982	Mar 11, 1986	Schlumberger Technology Corporation	Indirect shearwave determination
US4594662	Sep 19, 1983	Jun 10, 1986	Schlumberger Technology Corporation	Diffraction tomography systems and methods with fixed detector arrays
US4636956	Mar 20, 1984	Jan 13, 1987	Societe Nationale Elf Aquitaine (Production)	Method and device for optimization of seismic data
US4675851	Sep 9, 1982	Jun 23, 1987	Western Geophysical Co.	Method for seismic exploration
US4686654	Jul 31, 1986	Aug 11, 1987	Western Geophysical Company Of America	Method for generating orthogonal sweep signals
US4707812	Dec 9, 1985	Nov 17, 1987	Atlantic Richfield Company	Method of suppressing vibration seismic signal correlation noise
US4715020	Oct 29, 1986	Dec 22, 1987	Western Atlas International, Inc.	Simultaneous performance of multiple seismic vibratory surveys
US4766574	Mar 31, 1987	Aug 23, 1988	Amoco Corporation	Method for depth imaging multicomponent seismic data
US4780856	Oct 30, 1986	Oct 25, 1988	Institut Francais Du Petrole	Off-shore seismic prospection method using a coded vibratory signal and a device for implementing this method
US4823326	Jun 23, 1987	Apr 18, 1989	The Standard Oil Company	Seismic data acquisition technique having superposed signals
US4924390	Feb 22, 1988	May 8, 1990	Conoco, Inc.	Method for determination of earth stratum elastic parameters using seismic energy
US4953657	Feb 14, 1989	Sep 4, 1990	Halliburton Geophysical Services, Inc.	Time delay source coding
US4969129	Sep 20, 1989	Nov 6, 1990	Texaco Inc.	Coding seismic sources
US4982374	Oct 23, 1989	Jan 1, 1991	Halliburton Geophysical Services, Inc.	Method of source coding and harmonic cancellation for vibrational geophysical survey sources
US5260911	May 28, 1991	Nov 9, 1993	Mason Iain M	Seismic surveying
US5469062	Mar 11, 1994	Nov 21, 1995	Baker Hughes, Inc.	Multiple depths and frequencies for simultaneous inversion of electromagnetic borehole measurements
			Exxon Production Research	Method for deriving reservoir lithology and fluid content

Cited Patent	Filing date	Publication date	Applicant	Title
US5677893	Jul 7, 1995	Oct 14, 1997	Schlumberger Technology Corporation	Method of processing seismic data
US5715213	Nov 13, 1995	Feb 3, 1998	Mobil Oil Corporation	High fidelity vibratory source seismic method using a plurality of vibrator sources
US5717655	Mar 28, 1997	Feb 10, 1998	Western Atlas International, Inc.	Method for providing uniform subsurface coverage in the presence of steep dips
US5719821	Sep 29, 1995	Feb 17, 1998	Atlantic Richfield Company	Method and apparatus for source separation of seismic vibratory signals
US5721710	Sep 20, 1996	Feb 24, 1998	Atlantic Richfield Company	High fidelity vibratory source seismic method with source separation
US5790473	Nov 13, 1995	Aug 4, 1998	Mobil Oil Corporation	High fidelity vibratory source seismic method for use in vertical seismic profile data gathering with a plurality of vibratory seismic energy sources
US5798982	Apr 29, 1996	Aug 25, 1998	The Trustees Of Columbia University In The City Of New York	Method for inverting reflection trace data from 3-D and 4-D seismic surveys and identifying subsurface fluid and pathways in and among hydrocarbon reservoirs based on impedance models
US5822269	Nov 13, 1995	Oct 13, 1998	Mobil Oil Corporation	Method for separation of a plurality of vibratory seismic energy source signals
US5838634	Dec 9, 1996	Nov 17, 1998	Exxon Production Research Company	Method of generating 3-D geologic models incorporating geologic and geophysical constraints
US5852588	May 12, 1997	Dec 22, 1998	Schlumberger Technology Corporation	Method of processing seismic data
US5878372	Mar 4, 1997	Mar 2, 1999	Western Atlas International, Inc.	Method for simultaneous inversion processing of well log data using a plurality of earth models
US5920828	Jun 2, 1997	Jul 6, 1999	Baker Hughes Incorporated	Quality control seismic data processing system
US5924049	Jan 30, 1998	Jul 13, 1999	Western Atlas International, Inc.	Methods for acquiring and processing seismic data
US5999488	Apr 27, 1998	Dec 7, 1999	Phillips Petroleum Company	Method and apparatus for migration by finite differences
US5999489	Mar 21, 1997	Dec 7, 1999	Tomoseis Inc.	High vertical resolution crosswell seismic imaging
US6005916	Nov 17, 1997	Dec 21, 1999	Techniscan, Inc.	Apparatus and method for imaging with wavefields using inverse scattering techniques
US6014342	Jul 16, 1997	Jan 11, 2000	Tomo Seis, Inc.	Method of evaluating a subsurface region using gather sensitive data discrimination
US6021094	Mar 5, 1999	Feb 1, 2000	Sandia Corporation	Method of migrating seismic records
US6028818	May 28, 1997	Feb 22, 2000	Schlumberger Technology Corporation	Method and apparatus for multiple seismic vibratory surveys
US6058073	Mar 30, 1999	May 2, 2000	Atlantic Richfield Company	Elastic impedance estimation for inversion of far offset seismic sections
US6125330	Aug 19, 1998	Sep 26, 2000	Schlumberger Technology Corporation	Method of determining the response caused by model alterations in seismic simulations
US6219621	Jun 25, 1999	Apr 17, 2001	Exxonmobil Upstream Research Co.	Sparse hyperbolic inversion of seismic data
US6225803	Oct 29, 1998	May 1, 2001	Baker Hughes Incorporated	NMR log processing using wavelet filter and iterative inversion
US6311133	Sep 30, 1999	Oct 30, 2001	Institut Francais Du Petrole	3D prestack seismic data migration method
US6317695	Mar 30, 2000	Nov 13, 2001	Nutec Sciences, Inc.	Seismic data processing method
US6327537	Jul 19, 1999	Dec 4, 2001	Luc T. Ikelle	Multi-shooting approach to seismic modeling and acquisition
US6374201	Jul 2, 1998	Apr 16, 2002	Institut Francais Du Petrole	Method for 3D modelling of the impedance of a heterogeneous medium
US6381543	Aug 8, 2000	Apr 30, 2002	Institut Francais Du Petrole	Method for forming a model of a geologic formation, constrained by dynamic and static data
US6388947	Sep 14, 1998	May 14, 2002	Tomoseis, Inc.	Multi-crosswell profile 3D imaging and method
US6480790	Oct 11, 2000	Nov 12, 2002	Exxonmobil Upstream Research Company	Process for constructing three-dimensional geologic models having adjustable geologic interfaces
US6522973	Oct 30, 2000	Feb 18, 2003	Institut Francais Du Petrole	Method for 2D or 3D modelling of a heterogeneous medium such as the subsoil described by one or more physical parameters
US6545944	May 30, 2001	Apr 8, 2003	Westerngeco L.L.C.	Method for acquiring and processing of data from two or more simultaneously fired sources
			Schlumberger Technology	

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Cited Patent	Filing date	Publication date	Applicant	Title
US6574564	Apr 9, 2001	Jun 3, 2003	Institut Francais Du Petrole	3D prestack seismic data migration method
US6593746	Jan 15, 2002	Jul 15, 2003	Larry G. Stolarczyk	Method and system for radio-imaging underground geologic structures
US6662147	Apr 12, 2000	Dec 9, 2003	Fournier Frederique	Method allowing to obtain an optimum model of a physical characteristic in a heterogeneous medium such as the subsoil
US6665615	Mar 26, 2001	Dec 16, 2003	Jason Geosystems B.V.	Method of estimating elastic and compositional parameters from seismic and echo-acoustic data
US6687619	Oct 17, 2001	Feb 3, 2004	Westerngeco, L.L.C.	Method of using cascaded sweeps for source coding and harmonic cancellation
US6687659	Mar 24, 2000	Feb 3, 2004	Conocophillips Company	Method and apparatus for absorbing boundary conditions in numerical finite-difference acoustic applications
US6704245	Dec 21, 2001	Mar 9, 2004	Institut Francais Du Petrole	Seismic prospecting method and device using simultaneous emission of seismic signals obtained by coding a signal by pseudo-random sequences
US6714867	Feb 9, 2001	Mar 30, 2004	Institut Francais Du Petrole	Method for seismic monitoring of an underground zone by simultaneous use of sererval vibroseismic sources
US6735527	Feb 26, 2003	May 11, 2004	Landmark Graphics Corporation	3-D prestack/poststack multiple prediction
US6754590	May 16, 2000	Jun 22, 2004	Westerngeco, L.L.C.	Seismic surveying method
US6766256	Feb 13, 2001	Jul 20, 2004	Schlumberger Technology Corporation	Processing simultaneous vibratory seismic data
US6826486	Apr 3, 2003	Nov 30, 2004	Schlumberger Technology Corporation	Methods and apparatus for predicting pore and fracture pressures of a subsurface formation
US6836448	Jan 19, 2001	Dec 28, 2004	Schlumberger Technology Corporation	System and method for seismic wavefield separation
US6842701	Feb 25, 2002	Jan 11, 2005	Westerngeco L.L.C.	Method of noise removal for cascaded sweep data
US6859734	Oct 6, 2003	Feb 22, 2005	Paradigm Geophysical Corporation	Method and system for limited frequency seismic imaging
US6865487	May 6, 2003	Mar 8, 2005	Total Fina Elf S.A.	Method for decimating seismic traces driven by the seismic path
US6865488	Jan 16, 2004	Mar 8, 2005	Westerngeco, L.L.C.	Method of using cascaded sweeps for source coding and harmonic cancellation
US6876928	Sep 26, 2003	Apr 5, 2005	Jason Geosystems B.V.	Method of estimating elastic and compositional parameters from seismic and echo-acoustic data
US6882938	Jul 30, 2003	Apr 19, 2005	Pgs Americas, Inc.	Method for separating seismic signals from two or more distinct sources
US6882958	Jun 28, 2001	Apr 19, 2005	National Instruments Corporation	System and method for curve fitting using randomized techniques
US6901333	Oct 27, 2003	May 31, 2005	Fugro N.V.	Method and device for the generation and application of anisotropic elastic parameters
US6903999	Jan 19, 2001	Jun 7, 2005	Schlumberger Technology Corporation	System and method for estimating seismic material properties
US6906981	Jul 17, 2002	Jun 14, 2005	Pgs Americas, Inc.	Method and system for acquiring marine seismic data using multiple seismic sources
US6927698	Jun 4, 2002	Aug 9, 2005	Larry G. Stolarczyk	Shuttle-in receiver for radio-imaging underground geologic structures
US6944546	Oct 1, 2003	Sep 13, 2005	Halliburton Energy Services, Inc.	Method and apparatus for inversion processing of well logging data in a selected pattern space
US6947843	Jul 25, 2002	Sep 20, 2005	Vetco Grey Controls Limited	Microseismic signal processing
US6970397	Jul 9, 2003	Nov 29, 2005	Gas Technology Institute	Determination of fluid properties of earth formations using stochastic inversion
US6977866	Jan 9, 2004	Dec 20, 2005	Conocophillps Company	Method and process for prediction of subsurface fluid and rock pressures in the earth
US6999880	Mar 11, 2004	Feb 14, 2006	The Regents Of The University Of California	Source-independent full waveform inversion of seismic data
US7046581	Nov 24, 2004	May 16, 2006	Shell Oil Company	Well-to-well tomography
US7050356	Mar 31, 2003	May 23, 2006	Westerngeco L.L.C.	Method of seismic surveying
US7069149	Dec 14, 2001	Jun 27, 2006	Chevron U.S.A. Inc.	Process for interpreting faults from a fault-enhanced 3-dimensional seismic attribute volume
US7072767	Apr 1, 2003	Jul 4, 2006	Conocophillips Company	Simultaneous inversion for source wavelet and AVO parameters from prestack seismic data

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Cited Patent	Filing date	Publication date	Applicant	Title
US7092823	Jul 31, 2003	Aug 15, 2006	Institut Francais Du Petrole	Method of forming a model representative of the distribution of a physical quantity in an underground zone, free of the effect of correlated noises contained in exploration data
US7110900	Apr 7, 2004	Sep 19, 2006	Westerngeco L.L.C.	Determination of waveguide parameters
US7184367	Feb 13, 2004	Feb 27, 2007	Exxonmobil Upstream Research Company	Method to convert seismic traces into petrophysical property logs
US7230879	Feb 12, 2005	Jun 12, 2007	Chevron U.S.A. Inc.	Method and apparatus for true relative amplitude correction of seismic data for normal moveout stretch effects
US7271747	May 10, 2006	Sep 18, 2007	Rice University	Method and apparatus for distributed compressed sensing
US7330799	Oct 28, 2004	Feb 12, 2008	Société de commercialisation des produits de la recherche appliquée-Socpra Sciences et Génie s.e.c.	Method and algorithm for using surface waves
US7337069	Jun 24, 2005	Feb 26, 2008	Institut Francais Du Petrole	Method of simulating the sedimentary deposition in a basin respecting the thicknesses of the sedimentary sequences
US7373251	Dec 22, 2004	May 13, 2008	Marathon Oil Company	Method for predicting quantitative values of a rock or fluid property in a reservoir using seismic data
US7373252	Nov 2, 2006	May 13, 2008	Western Geco L.L.C.	3D pre-stack full waveform inversion
US7376046	Oct 11, 2006	May 20, 2008	Westerngeco L.L.C.	Method of seismic surveying
US7376539	Apr 16, 2003	May 20, 2008	Norsar	Method for simulating local prestack depth migrated seismic images
US7400978	Dec 18, 2006	Jul 15, 2008	Institute Francais Du Petrole	Method for updating a geologic model by seismic data
US7436734	Feb 13, 2004	Oct 14, 2008	Exxonmobil Upstream Research Co.	Shaped high frequency vibratory source
US7480206	Sep 13, 2004	Jan 20, 2009	Chevron U.S.A. Inc.	Methods for earth modeling and seismic imaging using interactive and selective updating
US7584056	Feb 22, 2006	Sep 1, 2009	Paradigm Geophysical Ltd.	Multiple suppression in angle domain time and depth migration
US7599798	Sep 11, 2007	Oct 6, 2009	Westerngeco L.L.C.	Migrating composite seismic response data to produce a representation of a seismic volume
US7602670	Nov 26, 2007	Oct 13, 2009	Westerngeco L.L.C.	Method of seismic surveying
US7616523	Nov 13, 2008	Nov 10, 2009	Pgs Geophysical As	Method for combining pressure and motion seismic signals from streamers where sensors are not at a common depth
US7620534	Apr 28, 2006	Nov 17, 2009	Saudi Aramco	Sound enabling computerized system for real time reservoir model calibration using field surveillance data
US7620536	Jul 15, 2005	Nov 17, 2009	Fujitsu Limited	Simulation techniques
US7646924	Aug 8, 2005	Jan 12, 2010	David Leigh Donoho	Method and apparatus for compressed sensing
US7672194	Dec 12, 2005	Mar 2, 2010	Westerngeco L.L.C.	Method of seismic surveying
US7672824	Dec 10, 2001	Mar 2, 2010	Westerngeco L.L.C.	Method for shallow water flow detection
US7675815	Jan 22, 2008	Mar 9, 2010	Spectraseis Ag	Time reverse reservoir localization
US7679990	Dec 6, 2004	Mar 16, 2010	Chevron U.S.A. Inc.	Methods for acquiring and processing seismic data from quasi-simultaneously activated translating energy sources
US7684281	Apr 14, 2008	Mar 23, 2010	Pgs Americas, Inc.	System for combining signals of pressure sensors and particle motion sensors in marine seismic streamers
US7710821	Aug 20, 2004	May 4, 2010	Schlumberger Technology Corporation	Multiple attenuation method
US7715985	Mar 23, 2007	May 11, 2010	Westerngeco L.L.C.	Method of evaluating the interaction between a wavefield and a solid body
US7715986	May 22, 2007	May 11, 2010	Chevron U.S.A. Inc.	Method for identifying and removing multiples for imaging with beams
US7725266	May 31, 2007	May 25, 2010	Bp Corporation North America Inc.	System and method for 3D frequency domain waveform inversion based on 3D time-domain forward modeling
US7791980	Jul 7, 2006	Sep 7, 2010	Westerngeco L.L.C.	Interpolation and extrapolation method for seismic recordings
US7835072	Mar 17, 2008	Nov 16, 2010	Sumitomo Electric Industries, Ltd.	Far-infrared camera lens, lens unit, and imaging

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Cited Patent	Filing date	Publication date	Applicant	Title
US7840625	Apr 7, 2006	Nov 23, 2010	California Institute Of Technology	Methods for performing fast discrete curvelet transforms of data
US7940601	Feb 26, 2007	May 10, 2011	Council Of Scientific & Industrial Research	Method for computing an exact impulse response of a plane acoustic reflector at zero offset due to a point acoustic source
US8121823	Sep 11, 2007	Feb 21, 2012	Exxonmobil Upstream Research Company	Iterative inversion of data from simultaneous geophysical sources
US8248886	Mar 19, 2008	Aug 21, 2012	Exxonmobil Upstream Research Company	Separation and noise removal for multiple vibratory source seismic data
US8379482 *	Jan 7, 2010	Feb 19, 2013	Exxonmobil Upstream Research Company	Using seismic attributes for data alignment and seismic inversion in joint PP/PS seismic analysis
US8428925	Jan 6, 2012	Apr 23, 2013	Exxonmobil Upstream Research Company	Iterative inversion of data from simultaneous geophysical sources
US8437998	Oct 13, 2010	May 7, 2013	Exxonmobil Upstream Research Company	Hybrid method for full waveform inversion using simultaneous and sequential source method
US8547794	Apr 8, 2010	Oct 1, 2013	Baker Hughes Incorporated	Extending the coverage of VSP/CDP imaging by using first-order downgoing multiples
US8688381	Sep 1, 2011	Apr 1, 2014	Exxonmobil Upstream Research Company	Simultaneous source inversion for marine streamer data with cross-correlation objective function
US8781748	Sep 9, 2011	Jul 15, 2014	Chevron U.S.A. Inc.	System and method for generating images of subsurface structures
US20020099504	May 15, 2001	Jul 25, 2002	Cross Timothy A.	Method of predicting three-dimensional stratigraphy using inverse optimization techniques
US20020120429	Dec 7, 2001	Aug 29, 2002	Peter Ortoleva	Methods for modeling multi-dimensional domains using information theory to resolve gaps in data and in theories
US20020169559	Mar 13, 2001	Nov 14, 2002	Onyia Ernest C.	Method and process for prediction of subsurface fluid and rock pressures in the earth
US20020183980	Mar 4, 2002	Dec 5, 2002	Patrice Guillaume	Methods of tomographically inverting picked events on migrated seismic data
US20040199330	Apr 1, 2003	Oct 7, 2004	Conocophillips Company	Simultaneous inversion for source wavelet and AVO parameters from prestack seismic data
US20040220743	Apr 30, 2003	Nov 4, 2004	Conocophillips Company	Method for determining shear-wave velocity model for depth migration of mode-converted data
US20040225483	Feb 24, 2004	Nov 11, 2004	Michal Okoniewski	Fdtd hardware acceleration system
US20040243313	Apr 23, 2004	Dec 2, 2004	Karine Broto	Method for determining a seismic wave velocity model in a heterogeneous underground
US20060235666	Dec 11, 2003	Oct 19, 2006	Assa Steven B	System and method for representing and processing and modeling subterranean surfaces
US20070036030	Aug 11, 2005	Feb 15, 2007	Baumel Robert T	Method of accounting for wavelet stretch in seismic data
US20070038691	Apr 7, 2006	Feb 15, 2007	Emmanuel Candes	Methods for performing fast discrete curvelet transforms of data
US20070274155	May 14, 2007	Nov 29, 2007	Ikelle Luc T	Coding and Decoding: Seismic Data Modeling, Acquisition and Processing
US20080175101	Jan 22, 2008	Jul 24, 2008	Spectraseis Ag	Time Reverse Reservoir Localization
US20080306692	Dec 21, 2005	Dec 11, 2008	Sondex Wireline Limited	Method and Apparatus for Determining the Permeability of Earth Formations
US20090067041	Mar 17, 2008	Mar 12, 2009	Sumitomo Electric Industries, Ltd.	Far-infrared camera lens, lens unit, and imaging apparatus
US20090070042	Aug 27, 2008	Mar 12, 2009	Richard Birchwood	Joint inversion of borehole acoustic radial profiles for in situ stresses as well as third-order nonlinear dynamic moduli, linear dynamic elastic moduli, and static elastic moduli in an isotropically stressed reference state
US20090083006	Aug 23, 2008	Mar 26, 2009	Randall Mackie	Methods and apparatus for three-dimensional inversion of electromagnetic data
US20090164186	Dec 20, 2007	Jun 25, 2009	Bhp Billiton Innovation Pty Ltd.	Method for determining improved estimates of properties of a model
US20090164756	Oct 18, 2006	Jun 25, 2009	Tor Dokken	Geological Response Data Imaging With Stream Processors
US20090187391	Jan 21, 2009	Jul 23, 2009	Schlumberger Technology Corporation	Three-dimensional mechanical earth modeling
				Simultaneous inversion of induction data for dielectric

Cited Patent	Filing date	Publication date	Applicant	Title
US20090254320	Mar 27, 2009	Oct 8, 2009	Andrea Lovatini	Joint inversion of time domain controlled source electromagnetic (td-csem) data and further data
US20090259406	Apr 8, 2009	Oct 15, 2009	Schlumberger Technology Corporation	Continuous microseismic mapping for real-time 3d event detection and location
US20090271118	Jun 6, 2006	Oct 29, 2009	Saltzer Rebecca L	Method for Obtaining Porosity and Shale Volume From Seismic Data
US20100008184	Jun 2, 2009	Jan 14, 2010	Stian Hegna	Method for aquiring and processing marine seismic data to extract and constructively use the up-going and down-going wave-fields emitted by the source(s)
US20100018718	Sep 11, 2007	Jan 28, 2010	Krebs Jerome R	Iterative inversion of data from simultaneous geophysical sources
US20100039894	Aug 17, 2009	Feb 18, 2010	Abma Raymond L	Method for separating independent simultaneous sources
US20100054082	Aug 29, 2008	Mar 4, 2010	Acceleware Corp.	Reverse-time depth migration with reduced memory requirements
US20100088035	Oct 6, 2009	Apr 8, 2010	Etgen John T	Pseudo-analytical method for the solution of wave equations
US20100103772	Oct 22, 2009	Apr 29, 2010	Conocophillips Company	Marine Seismic Acquisition
US20100118651	Sep 24, 2009	May 13, 2010	Chevron U.S.A. Inc.	Method for generation of images related to a subsurface region of interest
US20100142316	Dec 7, 2008	Jun 10, 2010	Henk Keers	Using waveform inversion to determine properties of a subsurface medium
US20100161233	Mar 7, 2010	Jun 24, 2010	Spectraseis Ag	Time Reverse Reservoir Localization
US20100161234	Mar 9, 2010	Jun 24, 2010	Spectraseis Ag	Time Reverse Reservoir Localization
US20100177595	Jan 7, 2010	Jul 15, 2010	Vijay Khare	Using Seismic Attributes for Data Alignment and Seismic Inversion In Joint PP/PS Seismic Analysis
US20100185422	Jan 20, 2009	Jul 22, 2010	Chevron U,S,A., Inc.	Stochastic inversion of geophysical data for estimating earth model parameters
US20100208554	Feb 11, 2010	Aug 19, 2010	Conocophillips Company	Multiple seismic signal inversion
US20100212909	Jan 8, 2010	Aug 26, 2010	Anatoly Baumstein	Method For Analyzing Multiple Geophysical Data Sets
US20100246324	Nov 5, 2009	Sep 30, 2010	Dragoset Jr William Henry	Multiple attenuation for ocean-bottom seismic data
US20100265797	Apr 17, 2009	Oct 21, 2010	Robertsson Johan O A	Interferometric seismic data processing
US20100270026	Dec 5, 2008	Oct 28, 2010	Spyridon Lazaratos	Spectral Shaping Inversion And Migration of Seismic Data
US20100286919	Jan 26, 2009	Nov 11, 2010	Sunwoong Lee	Characterizing Spatial Variability of Surface Waves In Seismic Processing
US20100299070	Aug 6, 2010	Nov 25, 2010	Bp Corporation North America Inc.	Method for separating independent simultaneous sources
US20110000678	Jan 26, 2009	Jan 6, 2011	Krebs Jerome R	Efficient Method For Inversion of Geophysical Data
US20110040926	Sep 5, 2009	Feb 17, 2011	Texas Memory Systems, Inc.	FLASH-based Memory System With Variable Length Page Stripes Including Data Protection Information
US20110051553	Mar 24, 2010	Mar 3, 2011	Ian Richard Scott	Determining the quality of a seismic inversion
US20110090760	Oct 19, 2009	Apr 21, 2011	James Rickett	Full-waveform inversion in the traveltime domain
US20110131020	Sep 9, 2010	Jun 2, 2011	Conocophillips Company	Dip guided full waveform inversion
US20110134722	Dec 6, 2010	Jun 9, 2011	Mediwound Ltd.	Simultaneous Joint Inversion of Surface Wave and Refraction Data
US20110182141	Aug 14, 2008	Jul 28, 2011	Schlumberger Technology Corporation	Method and system for monitoring a logging tool position in a borehole
US20110182144	Jan 24, 2011	Jul 28, 2011	Gray Frederick D	Methods and systems for estimating stress using seismic data
US20110191032	Jan 29, 2010	Aug 4, 2011	Ian Moore	Interpolation of periodic data
US20110194379	Jan 4, 2011	Aug 11, 2011	Sunwoong Lee	Methods For Subsurface Parameter Estimation In Full Wavefield Inversion And Reverse-Time Migration
US20110222370	Mar 11, 2011	Sep 15, 2011	Jon Downton	Methods and systems for performing azimuthal simultaneous elastic inversion
US20110227577	Mar 19, 2010	Sep 22, 2011	Schlumberger Technology Corporation	Single well reservoir imaging apparatus and methods
US20110235464	Mar 24, 2010	Sep 29, 2011	John Brittan	Method of imaging the earth's subsurface during marine seismic data acquisition
US20110238390	Feb 3, 2011	Sep 29, 2011	Krebs Jerome R	Full Wavefield Inversion Using Time Varying Filters

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Cited Patent	Filing date	Publication date	Applicant	Title
US20110267921	Apr 30, 2010	Nov 3, 2011	Schlumberger Technology Corporation	Multicomponent seismic inversion of vsp data
US20110267923	Sep 24, 2010	Nov 3, 2011	Snu R&Db Foundation	Apparatus and method for seismic imaging using waveform inversion solved by conjugate gradient least squares method
US20110276320	Mar 10, 2011	Nov 10, 2011	Krebs Jerome R	Artifact Reduction In Iterative Inversion Of Geophysical Data
US20110288831	Feb 24, 2011	Nov 24, 2011	Lijian Tan	Method and system for checkpointing during simulations
US20110299361	Feb 17, 2010	Dec 8, 2011	Changsoo Shin	Apparatus and method for imaging subsurface structure
US20110320180	May 13, 2011	Dec 29, 2011	Al-Saleh Saleh M	Migration Velocity Analysis of Seismic Data Using Common Image Cube and Green's Functions
US20120010862	Jul 11, 2011	Jan 12, 2012	Fumie Costen	Wave modelling
US20120014215	Sep 25, 2011	Jan 19, 2012	Spectraseis Ag	Time reverse reservoir localization with borehole data
US20120014216	Sep 25, 2011	Jan 19, 2012	Spectraseis Ag	Time reverse reservoir localization
US20120051176	Aug 31, 2010	Mar 1, 2012	Chevron U.S.A. Inc.	Reverse time migration back-scattering noise removal using decomposed wavefield directivity
US20120051177 *	Nov 2, 2011	Mar 1, 2012	Board Of Regents Of The University Of Texas System	Extracting sv shear data from p-wave seismic data
US20120073824	Oct 13, 2010	Mar 29, 2012	Routh Partha S	Hybride Method For Full Waveform Inversion Using Simultaneous and Sequential Source Method
US20120073825	Sep 9, 2011	Mar 29, 2012	Routh Partha S	Simultaneous Source Encoding and Source Separation As A Practical Solution For Full Wavefield Inversion
US20120082344	Dec 12, 2011	Apr 5, 2012	David Leigh Donoho	Method and apparatus for compressed sensing
US20120143506	Sep 1, 2011	Jun 7, 2012	Routh Partha S	Simultaneous Source Inversion for Marine Streamer Data With Cross-Correlation Objective Function
US20120215506	Feb 10, 2012	Aug 23, 2012	Rickett James E	Waveform inversion by multiple shot-encoding for non-fixed spread geometries
US20120218859	May 4, 2012	Aug 30, 2012	Cggveritas Services Sa	Method and Device for Processing Seismic Data
US20120275264	Jul 2, 2012	Nov 1, 2012	Westerngeco L.L.C.	Removing free-surface effects from seismic data acquired in a towed survey
US20120275267	Mar 26, 2012	Nov 1, 2012	Ramesh Neelamani	Seismic Data Processing
US20120290214	May 10, 2012	Nov 15, 2012	Saudi Arabian Oil Company	Coupled time-distance dependent swept frequency source acquisition design and data de-noising
US20120314538	Jun 8, 2011	Dec 13, 2012	Chevron U.S.A. Inc.	System and method for seismic data inversion
US20120316790	Jun 8, 2011	Dec 13, 2012	Chevron U.S.A. Inc.	System and method for data inversion with phase extrapolation
US20120316844	Jun 8, 2011	Dec 13, 2012	Chevron U.S.A. Inc.	System and method for data inversion with phase unwrapping
US20130081752	Jun 1, 2011	Apr 4, 2013	Denki Kagaku Kogyo Kabushiki Kaisha	Method of manufacturing translucent rigid substrate laminate
US20130238246	Jan 23, 2013	Sep 12, 2013	Jerome R. Krebs	Orthogonal Source and Receiver Encoding
US20130279290	Apr 9, 2013	Oct 24, 2013	Cggveritas Services Sa	Device and method for deghosting variable depth streamer data
US20130282292	Mar 18, 2013	Oct 24, 2013	Cggveritas Services Sa	Premigration deghosting of seismic data with a bootstrap technique
US20130311149	Mar 22, 2013	Nov 21, 2013	Yaxun Tang	Tomographically Enhanced Full Wavefield Inversion
US20130311151	Sep 27, 2011	Nov 21, 2013	René-Edouard André Michel Plessix	Earth model estimation through an acoustic full waveform inversion of seismic data
CA2796631A1	Mar 14, 2011	Nov 24, 2011	Exxonmobil Upstream Research Company	Method and system for checkpointing during simulations
EP1094338A1	Oct 22, 1999	Apr 25, 2001	Jason Geosystems B.V.	Method of estimating elastic parameters and rock composition of underground formations using seismic data
EP1746443A1	Oct 22, 1999	Jan 24, 2007	Jason Geosystems B.V.	Method of estimating elastic parameters and rock composition of underground formations using seismic data
GB2390712A				*Title not available*
GB2391665A				*Title not available*

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Cited Patent	Filing date	Publication date	Applicant	Title
WO2006037815A1	Oct 10, 2005	Apr 13, 2006	Compagnie Generale De Geophysique	Improvement to seismic processing for the elimination of multiple reflections
WO2007046711A1	Oct 18, 2006	Apr 26, 2007	Sinvent As	Geological response data imaging with stream processors
WO2008042081A1	Sep 11, 2007	Apr 10, 2008	Exxonmobil Upstream Research Company	Iterative inversion of data from simultaneous geophysical sources
WO2008123920A1	Mar 19, 2008	Oct 16, 2008	Exxonmobil Upstream Research Company	Separation and noise removal for multiple vibratory source seismic data
WO2009067041A1	May 26, 2008	May 28, 2009	Steklov Mathematical Institute Ras	Method and system for evaluating the characteristic properties of two contacting media and of the interface between them based on mixed surface waves propagating along the interface
WO2009117174A1	Jan 26, 2009	Sep 24, 2009	Exxonmobil Upstream Research Company	An efficient method for inversion of geophysical data
WO2010085822A2	Jan 26, 2010	Jul 29, 2010	Shotspotter, Inc.	Systems and methods with improved three-dimensional source location processing including constraint of location solutions to a two-dimensional plane
WO2011040926A1	Oct 1, 2009	Apr 7, 2011	Halliburton Energy Services, Inc.	Apparatus and methods of locating downhole anomalies
WO2011091216A2	Jan 21, 2011	Jul 28, 2011	Schlumberger Canada Limited	Real-time formation anisotropy and dip evaluation using tri-axial induction measurements
WO2011093945A1	Dec 2, 2010	Aug 4, 2011	Exxonmobil Upstream Research Company	Temporary field storage of gas to optimize field development
WO2012024025A1	Jun 27, 2011	Feb 23, 2012	Exxonmobil Upstream Research Company	Reducing the dimensionality of the joint inversion problem
WO2012041834A1	Sep 27, 2011	Apr 5, 2012	Shell Internationale Research Maatschappij B.V.	Earth model estimation through an acoustic full waveform inversion of seismic data
WO2012047384A1	Aug 19, 2011	Apr 12, 2012	Exxonmobil Upstream Research Company	Hybrid method for full waveform inversion using simultaneous and sequential source method
WO2012083234A2	Dec 16, 2011	Jun 21, 2012	Bp Corporation North America Inc.	Seismic acquisition using narrowband seismic sources
WO2012134621A1	Jan 30, 2012	Oct 4, 2012	Exxonmobil Upstream Research Company	Convergence rate of full wavefield inversion using spectral shaping
WO2012170201A2	May 23, 2012	Dec 13, 2012	Chevron U.S.A. Inc.	System and method for seismic data inversion by non-linear model update
WO2013081752A2	Oct 26, 2012	Jun 6, 2013	Exxonmobil Upstream Research Company	Methods for approximating hessian times vector operation in full wavefield inversion

* Cited by examiner

References

1   Abt, D.L. et al. (2010), "North American lithospheric discontinuity structured imaged by Ps And Sp receiver functions", J. Geophys. Res., 24 pgs.

2   Akerberg, P., et al. (2008), "Simultaneous source separation by sparse radon transform," 78th SEG Annual International Meeting, Expanded Abstracts, pp. 2801-2805.

3   Aki et al. (1980), "Quantitative Seismology, Theory and Methods," Chapter 5.20, W.H. Freeman & Co., pp. 133-155.

4   Aki, K. et al. (1980), "Quantitative Seismology: Theory and Methods vol. I," W.H. Freeman and Co., p. 173.

5   Aki, K. et al. (1980), "Quantitative Seismology: Theory and Methods vol. I-Chapter 7-Surface Waves in a Vertically Heterogenous Medium," W.H. Freeman and Co., pp. 259-318.

6   Aki, K. et al. (1980), "Quantitative Seismology: Theory and Methods vol. I—Chapter 7—Surface Waves in a Vertically Heterogenous Medium," W.H. Freeman and Co., pp. 259-318.

7   Amundsen, L. (2001), "Elimination of free-surface related multiples without need of the source wavelet," Geophysics 60(1), pp. 327-341.

8   Anderson, J.E. et al. (2008), "Sources Near the Free-Surface Boundary: Pitfalls for Elastic Finite-Difference Seismic Simulation and Multi-Grid Waveform Inversion," 70th EAGE Conf. & Exh., 4 pgs.

9   Barr, F.J. et al. (1989), "Attenuation of Water-Column Reverberations Using Pressure and Velocity Detectors in a Water-Bottom Cable," 59th Annual SEG meeting, Expanded Abstracts, pp. 653-656.

10   Baumstein, A. et al. (2009), "Scaling of the Objective Function Gradient for Full Wavefield Inversion," SEG Houston 2009 Int'l. Expo and Annual Meeting, pp. 224-2247.

11   Beasley, C. (2008), "A new look at marine simultaneous sources," The Leading Edge 27(7), pp. 914-917.

12   Beasley, C. (2012), "A 3D simultaneous source field test processed using alternating projections: a new active separation method," Geophsyical Prospecting 60, pp. 591-601.

14	Beaty, K.S. et al. (2003), "Repeatability of multimode Rayleigh-wave dispersion studies," Geophysics 68(3), pp. 782-790.
15	Becquey, M. et al. (2002), "Pseudo-Random Coded Simultaneous Vibroseismics," SEG Int'l. Exposition and 72th Annl. Mtg., 4 pgs.
16	Ben-Hadj-Ali, H. et al. (2009), "Three-dimensional frequency-domain full waveform inversion with phase encoding," SEG Expanded Abstracts, pp. 2288-2292.
17	Ben-Hadj-Ali, H. et al. (2011), "An efficient frequency-domain full waveform inversion method using simultaneous encoded sources," Geophysics 76(4), pp. R109-R124.
18	Benitez, D. et al. (2001), "The use of the Hilbert transform in ECG signal analysis," Computers in Biology and Medicine 31, pp. 399-406.
19	Berenger, J-P. (1994), "A Perfectly Matched Layer for the Absorption of Electromagnetic Waves," J. of Computational Physics 114, pp. 185-200.
20	Berkhout, A.J. (1987), "Applied Seismic Wave Theory," Elsevier Science Publishers, p. 142.
21	Berkhout, A.J. (1992), "Areal shot record technology," Journal of Seismic Exploration 1, pp. 251-264.
22	Berkhout, A.J. (2008), "Changing the mindset in seismic data acquisition," The Leading Edge 27(7), pp. 924-938.
23	Beylkin, G (1985), "Imaging of discontinuities in the inverse scattring problem by inversion of a causal generalized Radon transform," J Math. Phys. 26, pp. 99-108.
24	Biondi, B. (1992), "Velocity estimation by beam stack," Geophysics 57(8), pp. 1034-1047.
25	Bonomi, E. et al. (2006), "Wavefield Migration plus Monte Carlo Imaging of 3D Prestack Seismic Data," Geophysical Prospecting 54, pp. 505-514.
26	Boonyasiriwat, C. et al. (2010), 3D Multisource Full-Waveform using Dynamic Random Phase Encoding, SEG Denver 2010 Annual Meeting, pp. 1044-1049.
27	Boonyasiriwat, C. et al. (2010), 3D Multisource Full-Waveform using Dynamic Random Phase Encoding, SEG Denver 2010 Annual Meeting, pp. 3120-3124.
28	Bunks, C., et al. (1995), "Multiscale seismic waveform inversion," Geophysics 60, pp. 1457-1473.
29	Burstedde, G. et al. (2009), "Algorithmic strategies for full waveform inversion: 1D experiments," Geophysics 74(6), pp. WCC17-WCC46.
30	Chavent, G. et al. (1999), "An optimal true-amplitude least-squares prestack depth-migration operator," Geophysics 64(2), pp. 508-515.
31	Choi, Y et al. (2012), "Application of multi-source waveform inversion to marine stream data using the global correlation norm," Geophysical Prospecting 60, pp. 748-758.
32	Choi, Y. et al. (2011), "Application of encoded multisource waveform inversion to marine-streamer acquisition based on the global correlation," 73rd EAGE Conference, Abstract, pp. F026.
33	Clapp, R.G. (2009), "Reverse time migration with random boundaries," SEG International Exposition and Meeting, Expanded Abstracts, pp. 2809-2813.
34	Dai, W. et al. (2010), "3D Multi-source Least-squares Reverse Time Migration," SEG Denver 2010 Annual Meeting, pp. 3120-3124.
35	Delprat-Jannaud, F. et al. (2005), "A fundamental limitation for the reconstruction of impedance profiles from seismic data," Geophysics 70(1), pp. R1-R14.
36	Dickens, T.A. et al. (2011), RTM angle gathers using Poynting vectors, SEG Expanded Abstracts 30, pp. 3109-3113.
37	Donerici, B. et al. (1005), "Improved FDTD Subgridding Algorithms via Digital Filtering and Domain Overriding," IEEE Transactions on Antennas and Propagation 53(9), pp. 2938-2951.
38	Downey, N. et al. (2011), "Random-Beam Full-Wavefield Inversion," 2011 San Antonio Annual Meeting, pp. 2423-2427.
39	Dunkin, J.W. et al. (1973), "Effect of Normal Moveout on a Seismic Pluse," Geophysics 38(4), pp. 635-642.
40	Dziewonski A. et al. (1981), "Preliminary Reference Earth Model", Phys. Earth Planet. Int. 25(4), pp. 297-356.
41	Ernst, F.E. et al. (2000), "Tomography of dispersive media," J Acoust. Soc. Am 108(1), pp. 105-116.
42	Ernst, F.E. et al. (2002), "Removal of scattered guided waves from seismic data," Geophysics 67(4), pp. 1240-1248.
43	Esmersoy, C. (1990), "Inversion of P and SV waves from multicomponent offset vertical seismic profiles", Geophysics 55(1), pp. 39-50.
44	Etgen, J.T. et al. (2007), "Computational methods for large-scale 3D acoustic finite-difference modeling: A tutorial," Geophysics 72(5), pp. SM223-SM230.
45	Fallat, M.R. et al. (1999), "Geoacoustic inversion via local, global, and hybrid algorithms," Journal of the Acoustical Society of America 105, pp. 3219-3230.
46	Fichtner, A. et al. (2006), "The adjoint method in seismology I. Theory," Physics of the Earth and Planetary Interiors 157, pp. 86-104.
47	Forbriger, T. (2003), "Inversion of shallow-seismic wavefields: I. Wavefield transformation," Geophys. J. Int. 153, pp. 719-734.
48	Gao, H. et al. (2008), "Implementation of perfectly matched layers in an arbitrary geometrical boundary for leastic wave modeling," Geophysics J. Int. 174, pp. 1029-1036.
49	Gibson, B. et al. (1984), "Predictive deconvolution and the zero-phase source," Geophysics 49(4), pp. 379-397.
50	Godfrey, R. J. et al. (1998), "Imaging the Foiaven Ghost," SEG Expanded Abstracts, 4 pgs.
51	Griewank, A. (1992), "Achieving logarithmic growth of temporal and spatial complexity in reverse automatic differentiation," 1 Optimization Methods and Software, pp. 35-54.
52	Griewank, A. (2000), Evaluating Derivatives: Principles and Techniques of Algorithmic Differentiation, Society for Industrial and Applied Mathematics, 49 pgs.
53	Griewank, A. et al. (1996), "Algorithm 755: A package for the automatic differentiation of algorithms written in C/C++," ACM Transactions on Mathematical Software 22(2), pp. 131-167.
54	Griewank, A. et al. (2000), "Algorithm 799: An implementation of checkpointing for the reverse or adjoint mode of computational differentiation," 26 ACM Transactions on Mathematical Software pp 19 45

55	Haber, E. et al. (2010), "An effective method for parameter estimation with PDE constraints with multiple right hand sides," Preprint-UBC http://www.math.ubc.ca/~haber/pubs/PdeOptStochV5.pdf.
56	Haber, E. et al. (2010), "An effective method for parameter estimation with PDE constraints with multiple right hand sides," Preprint—UBC http://www.math.ubc.ca/~haber/pubs/PdeOptStochV5.pdf.
57	Hampson, D.P. et al. (2005), "Simultaneous inversion of pre-stack seismic data," SEG 75th Annual Int'l. Meeting, Expanded Abstracts, pp. 1633-1637.
58	Heinkenschloss, M. (2008), :"Numerical Solution of Implicity Constrained Optimization Problems," CAAM Technical Report TR08-05, 25 pgs.
59	Helbig, K. (1994), "Foundations of Anisotropy for Exploration Seismics," Chapter 5, pp. 185-194.
60	Herrmann, F.J. (2010), "Randomized dimensionality reduction for full-waveform inversion," EAGE abstract G001, EAGE Barcelona meeting, 5 pgs.
61	Holschneider, J. et al. (2005), "Characterization of dispersive surface waves using continuous wavelet transforms," Geophys. J. Int. 163, pp. 463-478.
62	Hu, L.Z. et al. (1987), "Wave-field transformations of vertical seismic profiles," Geophysics 52, pp. 307-321.
63	Huang, Y. et al. (2012), "Multisource least-squares migration of marine streamer and land data with frequency-division encoding," Geophysical Prospecting 60, pp. 663-680.
64	Igel, H. et al. (1996), "Waveform inversion of marine reflection seismograms for P impedance and Poisson's ratio," Geophys. J. Int. 124, pp. 363-371.
65	Ikelle, L.T. (2007), "Coding and decoding: Seismic data modeling, acquisition, and processing," 77th Annual Int'l. Meeting, SEG Expanded Abstracts, pp. 66-70.
66	International Search Report, PCT/US2014/037122, dated Oct. 22, 2014.
67	Jackson, D.R. et al. (1991), "Phase conjugation in underwater acoustics," J. Acoust. Soc. Am. 89(1), pp. 171-181.
68	Jing, X. et al. (2000), "Encoding multiple shot gathers in prestack migration," SEG International Exposition and 70th Annual Meeting Expanded Abstracts, pp. 786-789.
69	Kennett, B.L.N. (1991), "The removal of free surface interactions from three-component seismograms", Geophys. J. Int. 104, pp. 153-163.
70	Kennett, B.L.N. et al. (1988), "Subspace methods for large inverse problems with multiple parameter classes," Geophysical J. 94, pp. 237-247.
71	Krebs, J.R. (2008), "Fast Full-wavefield seismic inversion using encoded sources," Geophysics 74(6), pp. WCC177-WCC188.
72	Krohn, C.E. (1984), "Geophone ground coupling," Geophysics 49(6), pp. 722-731.
73	Kroode, F.T. et al. (2009), "Wave Equation Based Model Building and Imaging in Complex Settings," OTC 20215, 2009 Offshore Technology Conf., Houston, TX, May 4-7, 2009, 8 pgs.
74	Kulesh, M. et al. (2008), "Modeling of Wave Dispersion Using Continuous Wavelet Transforms II: Wavelet-based Frequency-velocity Analysis," Pure Applied Geophysics 165, pp. 255-270.
75	Lancaster, S. et al. (2000), "Fast-track 'colored' inversion," 70th SEG Ann. Meeting, Expanded Abstracts, pp. 1572-1575.
76	Lancaster, S. et al. (2000), "Fast-track 'colored' inversion," 70th SEG Ann. Meeting, Expanded Abstracts, pp. 1572-1575.
77	Lazaratos, S. (2006), "Spectral Shaping Inversion for Elastic and Rock Property Estimation," Research Disclosure, Issue 511, pp. 1453-1459.
78	Lazaratos, S. et al. (2009), "Inversion of Pre-migration Spectral Shaping," 2009 SEG Houston Int'l. Expo. & Ann. Meeting, Expanded Abstracts, pp. 2383-2387.
79	Lazaratos, S. et al. (2011), "Improving the convergence rate of full wavefield inversion using spectral shaping," SEG Expanded Abstracts 30, pp. 2428-2432.
80	Lecomte, I. (2008), "Resolution and illumination analyses in PSDM: A ray-based approach," The Leading Edge, pp. 650-663.
81	Lee, S. et al. (2010), "Subsurface parameter estimation in full wavefield inversion and reverse time migration," SEG Denver 2010 Annual Meeting, pp. 1065-1069.
82	Levanon, N. (1988), "Radar Principles," Chpt. 1, John Whiley & Sons, New York, pp. 1-18.
83	Liao, Q. et al. (1995), "2.5D full-wavefield viscoacoustic inversion," Geophysical Prospecting 43, pp. 1043-1059.
84	Liu, F. et al. (2007), "Reverse-time migration using one-way wavefield imaging condition," SEG Expanded Abstracts 26, pp. 2170-2174.
85	Liu, F. et al. (2011), "An effective imaging condition for reverse-time migration using wavefield decomposition," Geophysics 76, pp. S29-S39.
86	Maharramov, M. et al. (2007) , "Localized image-difference wave-equation tomography," SEG Annual Meeting, Expanded Abstracts, pp. 3009-3013.
87	Malmedy, V. et al. (2009), "Approximating Hessians in unconstrained optimization arising from discretized problems," Computational Optimization and Applications, pp. 1-16.
88	Marcinkovich, C. et al. (2003), "On the implementation of perfectly matched layers in a three-dimensional fourth-order velocity-stress finite difference scheme," J. of Geophysical Research 108(B5), 2276.
89	Martin, G.S. et al. (2006), "Marmousi2: An elastic upgrade for Marmousi," The Leading Edge, pp. 156-166.
90	Meier, M.A. et al. (2009), "Converted wave resolution," Geophysics, 74(2):doi:10.1190/1.3074303, pp. Q1-Q16.
91	Moghaddam, P.P. et al. (2010), "Randomized full-waveform inversion: a dimenstionality-reduction approach," 80th SEG Ann. Meeting, Expanded Abstracts, pp. 977-982.
92	Mora, P. (1987), "Elastic Wavefield Inversion," PhD Thesis, Stanford University, pp. 22-25.
93	Mora, P. (1987), "Nonlinear two-dimensional elastic inversion of multi-offset seismic data," Geophysics 52, pp. 1211-1228.
94	Mora, P. (1989), "Inversion = migration + tomography," Geophysics 64, pp. 888-901.

96	Neelamani, R. (2009), "Efficient seismic forward modeling using simultaneous sources and sparsity," SEG Expanded Abstracts, pp. 2107-2111.
97	Neelamani, R., (2008), "Simultaneous sourcing without compromise," 70th Annual Int'l. Conf. and Exh., EAGE, 5 pgs.
98	Nocedal, J. et al. (2000), "Numerical Optimization-Calculating Derivatives," Chapter 8, Springer Verlag, pp. 194-199.
99	Nocedal, J. et al. (2006), "Numerical Optimization, Chapt. 7-Large-Scale Unconstrained Optimization," Springer, New York, 2nd Edition, pp. 165-176.
100	Nocedal, J. et al. (2006), "Numerical Optimization, Chapt. 7—Large-Scale Unconstrained Optimization," Springer, New York, 2nd Edition, pp. 165-176.
101	Ostmo, S. et al. (2002), "Finite-difference iterative migration by linearized waveform inversion in the frequency domain," SEG Int'l. Expo. & 72nd Ann. Meeting, 4 pgs.
102	Park, C.B. et al. (1999), "Multichannel analysis of surface waves," Geophysics 64(3), pp. 800-808.
103	Park, C.B. et al. (2007), "Multichannel analysis of surface waves (MASW)-active and passive methods," The Leading Edge, pp. 60-64.
104	Park, C.B. et al. (2007), "Multichannel analysis of surface waves (MASW)—active and passive methods," The Leading Edge, pp. 60-64.
105	Pica, A. et al. (2005), "3D Surface-Related Multiple Modeling, Principles and Results," 2005 SEG Ann. Meeting, SEG Expanded Abstracts 24, pp. 2080-2083.
106	Plessix, R.E. et al. (2004), "Frequency-domain finite difference amplitude preserving monition," Geophys. J. Int. 157, pp. 975-987.
107	Porter, R.P. (1989), "Generalized holography with application to inverse scattering inverse source problems," In E. Wolf, editor, Progress in Optics XXVII, Elsevier, pp. 317-397.
108	Pratt, R.G. (1999), "Seismic waveform inversion in the frequency domain, Part 1: Theory and verification in a physical scale model," Geophysics 64, pp. 888-901.
109	Pratt, R.G. et al. (1998), "Gauss-Newton and full Newton methods in frequency-space seismic waveform inversion," Geophys. J. Int. 133, pp. 341-362.
110	Rawlinson, N. et al. (2008), "A dynamic objective function technique for generating multiple solution models in seismic tomography," Geophys. J. Int. 178, pp. 295-308.
111	Rayleigh, J.W.S. (1899), "On the transmission of light through an atmosphere containing small particles in suspension, and on the origin of the blue of the sky," Phil. Mag. 47, pp. 375-384.
112	Romero, L.A. et al. (2000), Phase encoding of shot records in prestack migration, Geophysics 65, pp. 426-436.
113	Ronen S. et al. (2005), "Imaging Downgoing waves from Ocean Bottom Stations," SEG Expanded Abstracts, pp. 963-967.
114	Routh, P. et al. (2011), "Encoded Simultaneous Source Full-Wavefield Inversion for Spectrally-Shaped Shaped Marine Streamer Data," SEG San Antonio 2011 Ann. Meeting, pp. 2433-2438.
115	Ryden, N. et al. (2006), "Fast simulated annealing inversion of surface waves on pavement using phase-velocity spectra," Geophysics 71(4), pp. R49-R58.
116	Sambridge, M.S. et al. (1991), "An Alternative Strategy for Non-Linear Inversion of Seismic Waveforms," Geophysical Prospecting 39, pp. 723-736.
117	Schoenberg, M. et al. (1989), "A calculus for finely layered anisotropic media," Geophysics 54, pp. 581-589.
118	Schuster, G.T. et al. (2010), "Theory of Multisource Crosstalk Reduction by Phase-Encoded Statics," SEG Denver 2010 Ann. Meeting, pp. 3110-3114.
119	Sears, T.J. et al. (2008), "Elastic full waveform inversion of multi-component OBC seismic data," Geophysical Prospecting 56, pp. 843-862.
120	Sheen, D-H. et al. (2006), "Time domain Gauss-Newton seismic waveform inversion in elastic media," Geophysics J. Int. 167, pp. 1373-1384.
121	Shen, P. et al. (2003), "Differential semblance velocity analysis by wave-equation migration," 73rd Ann. Meeting of Society of Exploration Geophysicists, 4 pgs.
122	Sheng, J. et al. (2006), "Early arrival waveform tomography on near-surface refraction data," Geophysics 71, pp. U47-U57.
123	Sheriff, R.E.et al. (1982), "Exploration Seismology", pp. 134-135.
124	Shih, R-C. et al. (1996), "Iterative pre-stack depth migration with velocity analysis," Terrestrial, Atmospheric & Oceanic Sciences 7(2), pp. 149-158.
125	Shin, C. et al. (2001), "Waveform inversion using a logarithmic wavefield," Geophysics 49, pp. 592-606.
126	Simard, P.Y. et al. (1990), "Vector Field Restoration by the Method of Convex Projections," Computer Vision, Graphics and Image Processing 52, pp. 360-385.
127	Sirgue, L. (2004), "Efficient waveform inversion and imaging: A strategy for selecting temporal frequencies," Geophysics 69, pp. 231-248.
128	Smith, G.C. et al. (1987), "Weighted Stacking for Rock Property Estimation and Detection of Gas," Geophysical Prospecting 35(5), pp. 993-1014.
129	Smith, G.C. et al., "Weighted Stacking for Rock Property Estimation and Detection of Gas," Geophysical Prospecting 35(9), pp. 993-1014, 1987.
130	Soubaras, R. et al. (2007), "Velocity model building by semblance maximization of modulated-shot gathers," Geophysics 72(5), pp. U67-U73.
131	Spitz, S. (2008), "Simultaneous source separation: a prediction-subtraction approach," 78th Annual Int'l. Meeting, SEG Expanded Abstracts, pp. 2811-2815.
132	Stefani, J. (2007), "Acquisition using simultaneous sources," 69th Annual Conf. and Exh., EAGE Extended Abstracts, 5 pgs.
133	Symes, W.W. (2007), "Reverse time migration with optimal checkpointing," Geophysics 72(5), pp. P.SM213-SM221.
134	Symes, W.W. (2009), "Interface error analysis for numerical wave propagation," Compu. Geosci. 13, pp. 363-371.
135	Tang, Y. (2008), "Wave-equation Hessian by phase encoding," SEG Expanded Abstracts 27, pp. 2201-205.

137	Tang, Y. et al. (2010), "Preconditioning full waveform inversion with phase-encoded Hessian," SEG Expanded Abstracts 29, pp. 1034-1037.
138	Tarantola, A. (1984), "Inversion of seismic reflection data in the acoustic approximation," Geophysics 49, pp. 1259-1266.
139	Tarantola, A. (1986), "A strategy for nonlinear elastic inversion of seismic reflection data," Geophysics 51(10), pp. 1893-1903.
140	Tarantola, A. (1988), "Theoretical background for the inversion of seismic waveforms, including elasticity and attenuation," Pure and Applied Geophysics 128, pp. 365-399.
141	Tarantola, A. (2005), "Inverse Problem Theory and Methods for Model Parameter Estimation," SIAM, pp. 79.
142	Trantham, E.C. (1994), "Controlled-phase acquisition and processing," SEG Expanded Abstracts 13, pp. 890-894.
143	Tsvankin, I. (2001), "Seismic Signatures and Analysis of Reflection Data in Anisotropic Media," Elsevier Science, p. 8.
144	U.S. Appl. No. 14/286,107, filed May 23, 2014, Hu et al.
145	U.S. Appl. No. 14/311,945, filed Jun. 20, 2014, Bansal et al.
146	U.S. Appl. No. 14/329,431, filed Jul. 11, 2014, Krohn et al.
147	U.S. Appl. No. 14/330,767, filed Jul. 14, 2014, Tang et al.
148	U.S. Appl. No. 25/272,827, filed May 8, 2014, Baumstein et al.
149	Valenciano, A.A. (2008), "Imaging by Wave-Equation Inversion," A Dissertation, Stanford University, 138 pgs.
150	van Groenestijn, G.J.A. et al. (2009), "Estimating primaries by sparse inversion and application to near-offset reconstruction," Geophyhsics 74(3), pp. A23-A28.
151	van Manen, D.J. (2005), "Making wave by time reversal," SEG International Exposition and 75th Annual Meeting, Expanded Abstracts, pp. 1763-1766.
152	Verschuur, D.J. (1989), "Wavelet Estimation by Prestack Multiple Elimination," SEG Expanded Abstracts 8, pp. 1129-1132.
153	Verschuur, D.J. (2009), Target-oriented, least-squares imaging of blended data, 79th Annual Int'l. Meeting, SEG Expanded Abstracts, pp. 2889-2893.
154	Verschuur, D.J. et al. (1992), "Adaptive surface-related multiple elimination," Geophysics 57(9), pp. 1166-1177.
155	Versteeg, R. (1994), "The Marmousi experience: Velocity model determination on a synthetic complex data set," The Leading Edge, pp. 927-936.
156	Vigh, D. et al. (2008), "3D prestack plane-wave, full-waveform inversion," Geophysics 73(5), pp. VE135-VE144.
157	Wang, K. et al. (2009), "Simultaneous full-waveform inversion for source wavelet and earth model," SEG Int'l. Expo. & Ann. Meeting, Expanded Abstracts, pp. 2537-2541.
158	Wang, Y. (2007), "Multiple prediction through inversion: Theoretical advancements and real data application," Geophysics 72(2), pp. V33-V39.
159	Weglein, A.B. (2003), "Inverse scattering series and seismic exploration," Inverse Problems 19, pp. R27-R83.
160	Wong, M. et al. (2010), "Joint least-squares inversion of up- and down-going signal for ocean bottom data sets," SEG Expanded Abstracts 29, pp. 2752-2756.
161	Wu R-S. et al. (2006), "Directional illumination analysis using beamlet decomposition and propagation," Geophysics 71(4), pp. S147-S159.
162	Xia, J. et al. (2004), "Utilization of high-frequency Rayleigh waves in near-surface geophysics," The Leading Edge, pp. 753-759.
163	Xie, X. et al. (2002), "Extracting angle domain information from migrated wavefield," SEG Expanded Abstracts21, pp. 1360-1363.
164	Xie, X.-B. et al. (2006), "Wave-equation-based seismic illumination analysis," Geophysics 71(5), pp. S169-S177.
165	Yang, K. et al. (2000), "Quasi-Orthogonal Sequences for Code-Division Multiple-Access Systems," IEEE Transactions on Information Theory 46(3), pp. 982-993.
166	Yoon, K. et al. (2004), "Challenges in reverse-time migration," SEG Expanded Abstracts 23, pp. 1057-1060.
167	Young, J. et al. (2011), "An application of random projection to parameter estimation in partial differential equations," SIAM, 20 pgs.
168	Zhang, Y. (2005), "Delayed-shot 3D depth migration," Geophysics 70, pp. E21-E28.
169	Ziolkowski, A. (1991), "Why don't we measure seismic signatures?," Geophysics 56(2), pp. 190-201.

CLASSIFICATIONS

International Classification	G01V1/28, G01V1/30
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