subterranean region. The depth of investigation is also typically computationally expensive and ambiguous to determine for any given set of seismic data.

[0009] One method for used in analyzing seismic data is a full-waveform inversion ("FWI"), which outputs a subsurface attribute model to use in calculating the seismic image. Geophysicists also sometimes perform an analysis of the depth of investigation of the velocity model from FWI - a factor in the depth of investigation and overall accuracy of the seismic image. FWI is computationally expensive, however.

[0010] As can be seen from the above discussion, the endeavor is computationally expensive in both time and resources. Significant benefits can therefore accrue in the course of seismic exploration activities by increasing efficiency in operation and usage of computational resources. While there are many techniques suitable for this purpose, the art is always open further advancements. The presently disclosed technique will therefore be well received.

Summary of the invention

[0010a] According to a first aspect of the present invention, there is provided a process for use in seismic exploration, including: obtaining a diving wave illumination image of a subterranean region from a set of seismic data representative of the subterranean region using a selected acquisition geometry in response to performing a reverse time migration on low frequency seismic data, wherein the selected acquisition geometry describes a location of a source and a location of a receiver; clipping an inverse of the diving wave illumination image to a range of values; performing a weighted full-waveform inversion on a subsurface attribute model of the subterranean region, including: weighting a full-waveform inversion gradient with the clipped inverse of the diving wave illumination image by multiplying the full-waveform inversion gradient by the clipped inverse of the diving wave illumination image; and performing the full-waveform inversion on parts of the subsurface attribute model corresponding to an area associated with the weighted gradient.

[0010b] According to a second aspect of the present invention, there is provided a process for use in seismic exploration, including: objectively quantifying a depth of investigation in a subterranean region for a selected acquisition geometry, wherein the selected acquisition geometry describes a location of a source and a location of a receiver; updating a subsurface attribute model for the subterranean region up to the objectively quantified depth of investigation, including: obtaining a diving wave

illumination image of the subterranean region from a set of seismic data representative of the subterranean region using the selected acquisition geometry in response to performing a reverse time migration on low frequency seismic data; clipping an inverse of the diving wave illumination image to a range of values; weighting a full-waveform inversion with the clipped inverse of the diving wave illumination image by multiplying the full-waveform inversion gradient by the clipped inverse of the diving wave illumination image; performing a full-waveform inversion on parts of the subsurface attribute model corresponding to an area associated with the weighted gradient; and iteratively performing subsequent weighted full-waveform inversions using differently weighted full-waveform inversion gradients to update the subsurface attribute model to depths deeper than the depth of investigation.

[0010c] According to a third aspect of the present invention, there is provided a method for use in seismic exploration, including: obtaining a given acquisition geometry, wherein the given acquisition geometry describes a location of a source and a location of a receiver; preconditioning a full-waveform inversion on a subsurface attribute model of a subterranean region using the given acquisition geometry by: obtaining a diving wave illumination image of the subterranean region from a set of seismic data representative of the subterranean region using the given acquisition geometry in response to performing a reverse time migration on low frequency seismic data; clipping an inverse of the diving wave illumination image to a range of values: and weighting a full-waveform inversion gradient with the clipped inverse of the diving wave illumination image by multiplying the full- waveform inversion gradient by the clipped inverse pf the diving wave illumination image; and performing the preconditioned full-waveform inversion on parts of the subsurface model corresponding to an area associated with the weighted gradient.

[0010d] According to a fourth aspect of the present invention, there is provided a process for use in seismic exploration, including: obtaining a diving wave illumination image of a subterranean region from a set of seismic data representative of the subterranean region using a selected acquisition geometry in response to performing a reverse time migration on low frequency seismic data, wherein the selected acquisition geometry describes a location of a source and a location of a receiver; clipping an inverse of the diving wave illumination image to a range of values; performing a weighted full-waveform inversion on a subsurface attribute model of the subterranean region, including: weighting a full-waveform inversion gradient with the clipped inverse of the diving wave illumination image by multiplying the full-waveform inversion gradient

by the clipped inverse of the diving wave; and performing the full-waveform inversion using the weighted gradient on parts of the subsurface attribute model corresponding to an area associated with the weighted gradient; and iteratively performing subsequent weighted full-waveform inversions using differently weighted full-waveform inversion gradients to upgrade the subsurface attribute model to depths deeper than the depths of investigation.

[0010e] According to a fifth aspect of the present invention, there is provided an apparatus, including: a storage; a communication medium; a processor communicating with the storage over the communication medium; a set of seismic data residing on the storage, the seismic data being representative of a subterranean region and obtained using a selected acquisition geometry, wherein the selected acquisition geometry describes a location of a source and a location of a receiver; a software component residing on the storage that, when executed by the processor, performs a process for use in seismic exploration, comprising: obtaining a diving wave illumination image of a subterranean region from the set of seismic data; clipping an inverse of the diving wave illumination image to a range of values; performing a weighted full-waveform inversion on a subsurface attribute model of the subterranean region, including: weighting a full-waveform inversion gradient with the clipped inverse of the diving wave illumination image by multiplying the full-waveform inversion gradient by the clipped inverse of the diving wave illumination image; and performing the full-waveform inversion on parts of the subsurface attribute model corresponding to an area associated with the weighted gradient.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] The accompanying drawings, which are incorporated herein and constitute a part of this specification, illustrate embodiments of the invention and together with the description, serve to explain the principles of the invention. In the figures:
[0012] Figure 1 graphically presents the process flow in the method of the technique disclosed herein.
[0013] Figure 2 graphically presents the process flow for obtaining a diving wave illumination image in one particular embodiment of the method of Figure 1.
[0014] Figure 3A-Figure 3B illustrate a computing apparatus that may be used to implement some aspects of the presently disclosed technique.

CLAIMS

1. A process for use in seismic exploration, comprising:

obtaining a diving wave illumination image of a subterranean region from a set of seismic data representative of the subterranean region using a selected acquisition geometry in response to performing a reverse time migration on low frequency seismic data, wherein the selected acquisition geometry describes a location of a source and a location of a receiver;

clipping an inverse of the diving wave illumination image to a range of values;

performing a weighted full-waveform inversion on a subsurface attribute model of the subterranean region, including:

weighting a full-waveform inversion gradient with the clipped inverse of the diving wave illumination image by multiplying the full-waveform inversion gradient by the clipped inverse of the diving wave illumination image; and

performing the full-waveform inversion on parts of the subsurface attribute model corresponding to an area associated with the weighted gradient.

2. The process of claim 1, wherein obtaining the diving wave illumination image includes retrieving a legacy diving wave illumination image from storage.

3. The process of claim 1, wherein obtaining the diving wave illumination image includes:

forward modeling on the subsurface attribute model to generate a set of synthetic, low frequency seismic data, the subsurface attribute model being generated from the data representative of the subterranean region;

performing a reverse time migration on the low frequency seismic data to obtain a plurality of gathers with large opening angles; and

stacking the gathers to yield the diving wave illumination image.

4. The process of claim 3, wherein the subsurface attribute model is a smooth subsurface attribute model.

5. The process of claim 3, wherein the low frequency seismic data are acquired by performing an acquisition between approximately 2 Hz – 6 Hz.

6. The process of claim 3, wherein the large opening angles comprise angles greater than approximately 160°.

7. The process of claim 3, wherein the subsurface attribute model comprises a velocity model.

8. The process of claim 3, wherein the subsurface attribute model is obtained from a set of seismic data.

9. The process of claim 1, further comprising clipping and weighted full-waveform inversion using a second range of values.

10. The process of claim 1, wherein clipping the inverse of the diving wave illumination image to the range of values includes clipping the inverse of the diving wave illumination image to a range of values between 0 and 1.

11. The process of claim 1, wherein performing the weighted full-waveform inversion includes performing a weighted full-waveform inversion with seismic data acquired from the subterranean region using the selected acquisition geometry.

12. The process of claim 1, wherein performing the weighted full-waveform inversion includes performing a weighted full-waveform inversion with synthetic seismic data acquired from a subsurface attribute model of the subterranean region using the selected acquisition geometry.

13. A process for use in seismic exploration, comprising:

objectively quantifying a depth of investigation in a subterranean region for a selected acquisition geometry, wherein the selected acquisition geometry describes a location of a source and a location of a receiver;

updating a subsurface attribute model for the subterranean region up to the objectively quantified depth of investigation, including:

obtaining a diving wave illumination image of the subterranean region from a set of seismic data representative of the subterranean region using the selected acquisition geometry in response to performing a reverse time migration on low frequency seismic data;

clipping an inverse of the diving wave illumination image to a range of values;

weighting a full-waveform inversion with the clipped inverse of the diving wave illumination image by multiplying the full-waveform inversion gradient by the clipped inverse of the diving wave illumination image;

performing a full-waveform inversion on parts of the subsurface attribute model corresponding to an area associated with the weighted gradient; and

iteratively performing subsequent weighted full-waveform inversions using differently weighted full-waveform inversion gradients to update the subsurface attribute model to depths deeper than the depth of investigation.

14. The process of claim 13, wherein obtaining the diving wave illumination image includes:

forward modeling on the subsurface attribute model to generate a set of synthetic, low frequency seismic data, the subsurface attribute model being generated from the data representative of the subterranean region;

performing a reverse time migration on the low frequency seismic data to obtain a plurality of gathers with large opening angles; and

stacking the gathers to yield the diving wave illumination image.

15. The process of claim 14, wherein the subsurface attribute model is a smooth subsurface attribute model.

16. The process of claim 14, wherein the low frequency seismic data are acquired by performing an acquisition between approximately 2 Hz – 6 Hz.

17. The process of claim 14, wherein the large opening angles comprise angles greater than approximately 160°.

18. A method for use in seismic exploration, comprising:

obtaining a given acquisition geometry, wherein the given acquisition geometry describes a location of a source and a location of a receiver;

preconditioning a full-waveform inversion on a subsurface attribute model of a subterranean region using the given acquisition geometry by:

obtaining a diving wave illumination image of the subterranean region from a set of seismic data representative of the subterranean region using the given acquisition geometry in response to performing a reverse time migration on low frequency seismic data;

clipping an inverse of the diving wave illumination image to a range of values: and

weighting a full-waveform inversion gradient with the clipped inverse of the diving wave illumination image by multiplying the full- waveform inversion gradient by the clipped inverse pf the diving wave illumination image; and

performing the preconditioned full-waveform inversion on parts of the subsurface model corresponding to an area associated with the weighted gradient.

19. The method of claim 18, wherein preconditioning the full-waveform inversion includes:

objectively quantifying a depth of investigation for the subsurface attribute model using the given acquisition.

20. A process for use in seismic exploration, comprising: obtaining a diving wave illumination image of a subterranean region from a set of seismic data representative of the subterranean region using a selected acquisition geometry in response to performing a reverse time migration on low frequency seismic data, wherein the selected acquisition geometry describes a location of a source and a location of a receiver;

clipping an inverse of the diving wave illumination image to a range of values;

performing a weighted full-waveform inversion on a subsurface attribute model of the subterranean region, including:

weighting a full-waveform inversion gradient with the clipped inverse of the diving wave illumination image by multiplying the full-waveform inversion gradient by the clipped inverse of the diving wave; and

performing the full-waveform inversion using the weighted gradient on parts of the subsurface attribute model corresponding to an area associated with the weighted gradient; and

iteratively performing subsequent weighted full-waveform inversions using differently weighted full-waveform inversion gradients to upgrade the subsurface attribute model to depths deeper than the depths of investigation.

21. The process of claim 20, wherein obtaining the diving wave illumination image includes:

forward modeling on the subsurface attribute model to generate a set of synthetic, low frequency seismic data, the subsurface attribute model being generated from the data representative of the subterranean region;

performing a reverse time migration on the low frequency seismic data to obtain a plurality of gathers with large opening angles; and

stacking the gathers to yield the diving wave illumination image.

22. The process of claim 21, wherein the subsurface attribute model is a smooth subsurface attribute model.

23. The process of claim 21, wherein the low frequency seismic data are acquired by performing an acquisition between approximately 2 Hz – 6 Hz.

24. The process of claim 21, wherein the large opening angles comprise angles greater than approximately 160°.

25. The process of claim 20, wherein clipping the inverse of the diving wave illumination image to the range of values includes clipping the inverse of the diving wave illumination image to a range of values between 0 and 1.

26. An apparatus, comprising:

a storage;

a communication medium;

a processor communicating with the storage over the communication medium;

a set of seismic data residing on the storage, the seismic data being representative of a subterranean region and obtained using a selected acquisition geometry, wherein the selected acquisition geometry describes a location of a source and a location of a receiver;

a software component residing on the storage that, when executed by the processor, performs a process for use in seismic exploration, comprising:

obtaining a diving wave illumination image of a subterranean region from the set of seismic data;

clipping an inverse of the diving wave illumination image to a range of values;

performing a weighted full-waveform inversion on a subsurface attribute model of the subterranean region, including:

weighting a full-waveform inversion gradient with the clipped inverse of the diving wave illumination image by multiplying the full-waveform inversion gradient by the clipped inverse of the diving wave illumination image; and

performing the full-waveform inversion on parts of the subsurface attribute model corresponding to an area associated with the weighted gradient.

27. The apparatus of claim 26, wherein obtaining the diving wave illumination image includes:

forward modeling on the subsurface attribute model to generate a set of synthetic, low frequency seismic data, the subsurface attribute model being generated from the data representative of the subterranean region;

performing a reverse time migration on the low frequency seismic data to obtain a plurality of gathers with large opening angles; and

stacking the gathers to yield the diving wave illumination image.

28. The apparatus of claim 27, wherein the subsurface attribute model is a smooth subsurface attribute model.

29. The apparatus of claim 27, wherein the low frequency seismic data are acquired by performing an acquisition between approximately 2 Hz – 6 Hz.

30. The apparatus of claim 27, wherein the large opening angles comprise angles greater than approximately 160°.

31. The apparatus of claim 26, wherein clipping the inverse of the diving wave illumination image to the range of values includes clipping the inverse of the diving wave illumination image to a range of values between 0 and 1.