

of strong deep primaries intersecting or overlapping with multiples in the selected window, it will now be possible to separate primary from multiple after step 105. Therefore, wavelet estimation in step 104 needs to be repeated, along with steps 101-106, in order to match simulated multiples with the multiples separated from deep primaries.

5 [0026] By repeating the process above, if necessary, the present inventive method will generate the optimal wavelet and subsurface model such that simulated primaries (shallow and deep), and multiples match recorded data. Notice that the concept of "shallow/deep primaries" and "multiples of interest" are defined recursively, i.e., "deep primary" will become "shallow primary" after "multiples of interest" are modeled and
10 separated, and the multiples that are "of interest" will be the strong multiples in the depth layer to which the model is being extended in the recursive sequence. Figure 13 illustrates this recursion. 131 shows the deep primary (lower - - - curve) masked by a multiple (solid line) generated from the shallow primary (upper - line). With the multiple thus revealed, it can be removed as shown in 132, where a multiple appearing at a greater depth can now be
15 modeled, and so on until all primaries are inverted. Thus, the whole process can be repeated until a final wavelet and subsurface model (107) are achieved.

[0027] The foregoing patent application 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
20 possible. All such modifications and variations are intended to be within the scope of the present invention, as defined in the appended claims.

References

- Tarantola, A., "Theoretical background for the inversion of seismic waveforms, including elasticity and attenuation," *Pure and Applied Geophysics* **128**, 365-399 (1988).
- 25 Delprat-Jannaud, F. et al., "A fundamental limitation for the reconstruction of impedance profiles from seismic data," *Geophysics* **70**, R1-R14 (2005).
- Wang, K. et. al., "Simultaneous full-waveform inversion for source wavelet and earth model," *SEG Expanded Abstract* **28**, 2537-2541, (2009).
- Verschuur, D.J. et al., "Wavelet estimation by prestack multiple elimination," *SEG*
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CLAIMS

1. A computer-implemented seismic processing method comprising generating and simultaneously optimizing a source wavelet and subsurface model to an extendable depth, wherein simulated waveforms of both primary reflections and multiple reflections are
5 generated from the source wavelet and the subsurface model in depth domain and are then compared for a match to waveforms as recorded at seismic receiver locations.
2. The method of claim 1, wherein said seismic processing method is a method for inversion of measured seismic data from a subsurface region to infer a model of a physical
10 property affecting propagation of seismic waves.
3. The method of claim 2, wherein said generating and simultaneously optimizing comprises:
- (a) selecting a shallow layer of the measured seismic data substantially consisting
15 of primary reflections arriving before first arrival of strong multiple reflections, "strong" being determined based on a preselected reflectivity threshold;
- (b) inverting the shallow layer using an estimated seismic source wavelet to generate synthetic data and optimizing a shallow physical property model in depth domain to match the measured data in the shallow window;
- 20 (c) simulating multiple reflection data based on the shallow physical property model and the estimated seismic source wavelet;
- (d) comparing the simulated multiple reflection data to the measured seismic data within a window selected to contain substantially only multiple reflection data, said comparison determining degree of mismatch;
- 25 (e) adjusting the estimated seismic source wavelet as necessary to reduce the mismatch and repeating (b)-(e) as necessary to simultaneously optimize the seismic source wavelet and the shallow physical property model in depth domain; and
- (f) subtracting the simulated multiple reflection data from the measured seismic data, then extending the shallow layer to a greater depth, and then repeating (b)-(e) for the
30 extended shallow layer.

4. The method of claim 3, further comprising further extending the physical property model's depth range by repeating (f) at least once.
- 5 5. The method of claim 3, wherein said adjusting the estimated seismic source wavelet comprises at least one of:
- applying a phase rotation to the estimated seismic source wavelet;
 - applying an amplitude correction factor to the estimated seismic source wavelet;
 - applying a spectral shaping filter to the estimated seismic source wavelet.
- 10 6. The method of claim 5, wherein the amplitude correction factor is amplitude of said simulated multiple reflection data divided by amplitude of said measured seismic data within a window selected to contain substantially only multiple reflection data
- 15 7. The method of claim 5, wherein the phase rotation is determined by varying the source wavelet's phase and repeating (b)-(d) and examining effect of the varied phase on the comparison in (d) for a water-bottom multiple reflection event or another seismic reflection event selected based on separation of multiple and primary reflections.
- 20 8. The method of claim 5, wherein the spectral shaping filter is designed based at least partly on an analysis of said mismatch in (d) for frequency content.
9. A computer program product, comprising a non-transitory computer usable medium having a computer readable program code embodied therein, said computer readable program code adapted to be executed to implement a method for estimating a source wavelet and a physical property model for a subsurface region from seismic data utilizing multiple reflections in the seismic data, said method comprising:
- 25 generating and simultaneously optimizing a source wavelet and subsurface model to an extendable depth, wherein simulated waveforms of both primary reflections and multiple

reflections are generated from the source wavelet and the subsurface model in depth domain and are then compared for a match to waveforms as recorded at seismic receiver locations.

of strong deep primaries intersecting or overlapping with multiples in the selected window, it will now be possible to separate primary from multiple after step 105. Therefore, wavelet estimation in step 104 needs to be repeated, along with steps 101-106, in order to match simulated multiples with the multiples separated from deep primaries.

[0026] By repeating the process above, if necessary, the present inventive method will generate the optimal wavelet and subsurface model such that simulated primaries (shallow and deep), and multiples match recorded data. Notice that the concept of "shallow/deep primaries" and "multiples of interest" are defined recursively, i.e., "deep primary" will become "shallow primary" after "multiples of interest" are modeled and separated, and the multiples that are "of interest" will be the strong multiples in the depth layer to which the model is being extended in the recursive sequence. Figure 13 illustrates this recursion. 131 shows the deep primary (lower - - - curve) masked by a multiple (solid line) generated from the shallow primary (upper - - - line). With the multiple thus revealed, it can be removed as shown in 132, where a multiple appearing at a greater depth can now be modeled, and so on until all primaries are inverted (133). Thus, the whole process can be repeated until a final wavelet and subsurface model (107) are achieved.

[0027] The foregoing patent application 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 in the appended claims.

References

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Verschuur, D.J. et al, "Wavelet estimation by prestack multiple elimination," *SEG Expanded Abstract* **8**, 1129-1 132, (1989).

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CLAIMS

1. A computer-implemented method for inversion of measured seismic data from a subsurface region comprising:

- (a) selecting a shallow layer from the measured seismic data with the layer's depth determined to include primary reflections (shallow primaries), but exclude first arrivals of multiple reflections of interest (multiples);
- (b) inverting the shallow primaries using an estimated seismic source wavelet to obtain a shallow model of a physical property affecting propagation of seismic waves;
- (c) computer-simulating the multiples using the inverted shallow model and the estimated seismic source wavelet;
- (d) comparing the simulated multiples to the corresponding multiples in the seismic data, and adjusting the estimated seismic source wavelet to reduce misfit;
- e) repeating (b) - (d) at least once, or until the misfit is reduced below a predetermined level or other stopping condition is met; and
- (f) outputting a simultaneously optimized seismic source wavelet and shallow model.

2. The method of claim 1, further comprising extending applicability of the shallow model and the seismic source wavelet to a greater depth by inserting after (e) and before (f) a step comprising:

- (e1) subtracting the simulated multiples from the seismic data, then extending the shallow layer to a greater depth, and then repeating (b) - (e) for the extended shallow layer.

3. The method of claim 2, wherein

the multiple reflections of interest-are strong multiples "strong" being determined based on a preselected reflectivity threshold;

the inverting of the shallow primaries comprises generating predicted data and optimizing the shallow model in depth domain to match the measured data in the shallow layer; and

the comparing the simulated multiples to corresponding multiples in the seismic data is performed within a window selected to contain multiples and to minimize overlapping between multiples and primaries.

4. The method of claim 3, further comprising further extending the physical property model's depth range by repeating (e1) at least once.

5. The method of claim 3, wherein said adjusting the estimated seismic source wavelet comprises at least one of:

applying a phase rotation to the estimated seismic source wavelet;

applying an amplitude correction factor to the estimated seismic source wavelet;

applying a spectral shaping filter to the estimated seismic source wavelet.

6. The method of claim 5, wherein the amplitude correction factor is amplitude of said simulated multiple reflection data divided by amplitude of said measured seismic data within a window selected to contain multiples and to minimize overlapping between multiples and primaries.

7. The method of claim 5, wherein the phase rotation is determined by varying the source wavelet's phase and repeating (b) - (d) and examining effect of the varied phase on the comparison in (d) for a water-bottom multiple reflection event or another seismic reflection event selected based on separation of multiple and primary reflections.

8. The method of claim 5, wherein the spectral shaping filter is designed based at least partly on an analysis of said mismatch in (d) for frequency content.

9. A computer program product, comprising a non-transitory computer usable medium having a computer readable program code embodied therein, said computer readable program code adapted to be executed to implement a method for optimizing a source wavelet and a physical property model for a subsurface region from seismic data utilizing multiple reflections in the seismic data, said method comprising:

- (a) selecting a shallow layer from the measured seismic data with the layer's depth determined to include primary reflections (shallow primaries), but exclude first arrivals of multiple reflections of interest (multiples);
- (b) inverting the shallow primaries using an estimated seismic source wavelet to obtain a shallow model of a physical property affecting propagation of seismic waves;
- (c) computer-simulating the multiples using the inverted shallow model and the estimated seismic source wavelet;
- (d) comparing the simulated multiples to the corresponding multiples in the seismic data, and adjusting the estimated seismic source wavelet to reduce misfit;
- e) repeating (b) - (d) at least once, or until the misfit is reduced below a predetermined level or other stopping condition is met; and
- (f) outputting a simultaneously optimized seismic source wavelet and shallow model.