

CLAIMS

1. A method for determining physical structure or a physical property of a subsurface earth region from seismic survey data by removing surface-wave noise from seismic data traces, said data traces corresponding to at least one source location and a plurality of receiver locations in a seismic survey of the subsurface region, said method comprising:
- 5
- (a) dividing a near-surface part of the subsurface region into one or more cells;
 - (b) simultaneously solving for at least two types of surface-consistent components of the seismic traces, wherein a surface-consistent component characterizes filtering effects either of propagation of a seismic surface wave mode across a cell (a propagation filter), or
10 due to generation of surface wave energy at a source location (a source filter) or due to receiving of surface wave energy at a receiver location (a receiver filter), and wherein a "type" of surface-consistent component is one of (i) a propagation filter for one surface wave mode, evaluated at all cells crossed by any of the seismic traces; (ii) a source filter, evaluated at all source locations for the seismic traces, or (iii) a receiver filter, evaluated at all receiver
15 locations for the seismic traces; and
 - (c) computing a surface-wave waveform using said surface-consistent components;
 - (d) transforming the seismic data by subtracting or adaptively subtracting or adaptively subtracting the computed surface-wave waveform from the seismic data traces;
20 and
 - (e) using the seismic data after surface-wave noise removal to determine physical structure or a physical property of a subsurface earth region of the subsurface earth region.
2. The method of claim 1, further comprising using the determined physical structure or physical property for hydrocarbon assessment of, or extraction from, the subsurface earth
25 region.
3. The method of claim 1, further comprising in (b), for some or all of the traces and corresponding seismic source and receiver locations, computing the raypath distance across each intervening cell from the source location to the receiver location, and wherein the solution for surface-consistent components optimizes said components by a single

comparison or iterated comparisons of data traces from the seismic survey and surface-wave predictions computed using assumed or iteratively updated components along with the computed raypath distances.

4. The method of claim 1, wherein the surface-consistent components are complex
5 functions of frequency, i.e. functions having a real part and an imaginary part.

5. The method of claim 1, wherein at least two distinct modes are identified in the seismic data, and the surface-consistent components include parameters for multi-mode propagation of surface-waves.

6. The method of claim 5, wherein the distinct modes are identified from the data after
10 the data are transformed into a frequency domain or a frequency-wavenumber domain.

7. The method of claim 1, wherein the surface-consistent components are also a function of azimuth or propagation direction.

8. The method of claim 1, wherein the surface-consistent components include parameters for velocity dispersion or attenuation.

15 9. The method of claim 1, wherein the solution is obtained in (c) by minimizing a cost function involving the sum over a group of traces of the difference between a model expression, which is a function of said surface-consistent components, and the survey data.

10. The method of claim 1, wherein a model optimization algorithm is used in solving for said surface-consistent components, wherein the model is a model of a waveform for either a
20 single ground roll mode or for multiple modes.

11. The method of claim 1, wherein solving for said surface-consistent components involves using one or more of constraints, damping, normalization, weights, and regularization.

12. The method of claim 1, wherein the seismic data are conditioned by windowing, by
25 filtering, by cross-correlation filtering, or by cross-correlation, then followed by stacking or by transforming the data into a domain other than the space-time domain in which the data were recorded.

13. The method of claim 4, wherein the complex surface-consistent components include source amplitude and phase, and a complex slowness for each cell crossed by the trace raypath and for each ground-roll mode being treated.

14. The method of claim 1, further comprising:

- (i) using the solution for the surface-consistent components to image or to invert for scattered surface waves;
- (ii) for each trace, computing scattered surface-wave waveforms; and
- (iii) subtracting or adaptively subtracting the scattered surface waves from the seismic data.

15. The method of claim 1, further comprising:

- (i) defining surface locations for scatterers of surface waves;
- (ii) for each trace and corresponding seismic source and receiver locations, computing the raypath distance across each intervening cell from the source location to one or more scatterer locations and then to the receiver location;
- (iii) solving for surface-consistent scatterer components for the scatterers that predict waveforms for scattered surface waves in the seismic data; and
- (iv) using in (d) said surface-consistent scatterer components together with the surface-consistent components from (c), thereby computing surface-wave waveforms that include both direct and scattered waves.

16. The method of claim 3, further comprising repeating steps (a)-(b) at least once, wherein the cell division in (a) is changed to improve consistency between predicted and survey data waveforms.

17. The method of claim 1, wherein the components for each trace consist of a source component, a receiver component, and a component for each cell crossed in the raypath from the source to the receiver.

18. A method for producing hydrocarbons from a subsurface region, comprising:

(a) obtaining physical structure or a physical property determined from data from a seismic survey of the subsurface region using a method as described in claim 1, which is incorporated herein by reference; and

(b) drilling a well into the subsurface region based at least in part on said physical structure or physical property, and producing hydrocarbons from the well.

19. A method for removing surface-wave noise from seismic data, comprising estimating a plurality of surface-consistent transfer functions in frequency domain, or impulse responses in time domain, that represent changes in surface wave waveforms as they propagate from source to receiver, and using the estimates to predict surface-wave waveforms, and then subtracting the predicted surface waves from the seismic data.

CLAIMS

1. A method for determining physical structure or a physical property of a subsurface earth region from seismic survey data by removing surface-wave noise from seismic data traces, said data traces corresponding to at least one source location and a plurality of receiver locations in a seismic survey of the subsurface region, said method comprising:
 - (a) dividing a near-surface part of the subsurface region into one or more cells;
 - (b) simultaneously solving for at least two types of surface-consistent components of the seismic traces, wherein a surface-consistent component characterizes filtering effects either of propagation of a seismic surface wave mode across a cell, called a propagation filter, or due to generation of surface wave energy at a source location, called a source filter or due to receiving of surface wave energy at a receiver location, called a receiver filter, and wherein a "type" of surface-consistent component is one of (i) a propagation filter for one surface wave mode, evaluated at all cells crossed by any of the seismic traces; (ii) a source filter, evaluated at all source locations for the seismic traces, or (iii) a receiver filter, evaluated at all receiver locations for the seismic traces; and
 - (c) computing a surface-wave waveform using said surface-consistent components;
 - (d) transforming the seismic data by subtracting or adaptively subtracting the computed surface-wave waveform from the seismic data traces; and
 - (e) using the seismic data after surface-wave noise removal to determine physical structure or a physical property of the subsurface earth region;wherein at least (b)-(d) are performed using a computer.
2. The method of claim 1, further comprising using the determined physical structure or physical property for hydrocarbon assessment of, or extraction from, the subsurface earth region.
3. The method of claim 1, further comprising in (b), for some or all of the traces and corresponding seismic source and receiver locations, computing the raypath distance across each intervening cell from the source location to the receiver location, and wherein the solution for surface-consistent components optimizes said components by a single comparison or iterated comparisons of data traces from the seismic survey and surface-wave

predictions computed using assumed or iteratively updated components along with the computed raypath distances.

4. The method of claim 1, wherein the surface-consistent components are complex functions of frequency, i.e. functions having a real part and an imaginary part.

5. The method of claim 1, wherein at least two distinct modes are identified in the seismic data, and the surface-consistent components include parameters for multi-mode propagation of surface-waves.

6. The method of claim 5, wherein the distinct modes are identified from the data after the data are transformed into a frequency domain or a frequency-wavenumber domain.

7. The method of claim 1, wherein the surface-consistent components are also a function of azimuth or propagation direction.

8. The method of claim 1, wherein the surface-consistent components include parameters for velocity dispersion or attenuation.

9. The method of claim 1, wherein the solution is obtained in (c) by minimizing a cost function involving the sum over a group of traces of the difference between a model expression, which is a function of said surface-consistent components, and the survey data.

10. The method of claim 1, wherein a model optimization algorithm is used in solving for said surface-consistent components, wherein the model is a model of a waveform for either a single ground roll mode or for multiple modes.

11. The method of claim 1, wherein solving for said surface-consistent components involves using one or more of constraints, damping, normalization, weights, and regularization.

12. The method of claim 1, wherein the seismic data are conditioned by windowing, by filtering, by cross-correlation filtering, or by cross-correlation, then followed by stacking or

by transforming the data into a domain other than the space-time domain in which the data were recorded.

13. The method of claim 4, wherein the complex surface-consistent components include source amplitude and phase, and a complex slowness for each cell crossed by the trace raypath and for each ground-roll mode being treated.

14. The method of claim 1, further comprising:

- (i) using the solution for the surface-consistent components to image or to invert for scattered surface waves;
- (ii) for each trace, computing scattered surface-wave waveforms; and
- (iii) subtracting or adaptively subtracting the scattered surface waves from the seismic data.

15. The method of claim 1, further comprising:

- (i) defining surface locations for scatterers of surface waves;
- (ii) for each trace and corresponding seismic source and receiver locations, computing the raypath distance across each intervening cell from the source location to one or more scatterer locations and then to the receiver location;
- (iii) solving for surface-consistent scatterer components for the scatterers that predict waveforms for scattered surface waves in the seismic data; and
- (iv) using in (d) said surface-consistent scatterer components together with the surface-consistent components from (c), thereby computing surface-wave waveforms that include both direct and scattered waves.

16. The method of claim 1, wherein at least one of the surface-consistent components is a transfer function in frequency domain or an impulse response in time domain.

17. The method of claim 3, further comprising repeating steps (a)-(b) at least once, wherein the cell division in (a) is changed to improve consistency between predicted and survey data waveforms.

18. The method of claim 1, wherein the components for each trace consist of a source component, a receiver component, and a component for each cell crossed in the raypath from the source to the receiver.

19. A method for producing hydrocarbons from a subsurface region, comprising:

- (a) obtaining physical structure or a physical property determined from data from a seismic survey of the subsurface region using a method as described in claim 1; and
- (b) drilling a well into the subsurface region based at least in part on said physical structure or physical property, and producing hydrocarbons from the well.

20. A method for removing surface-wave noise from seismic data, comprising estimating a plurality of surface-consistent transfer functions in frequency domain, or alternatively estimating impulse responses in time domain, that characterize changes in surface wave waveforms caused by filtering effects as they are transmitted by a source and are propagated through a medium to be recorded at a receiver, and using the estimates to predict surface-wave waveforms using a computer, and then subtracting the predicted surface waves from the seismic data.