CLAIMS

1. In a process for generating an image of a subterranean formation using marine seismic techniques in which one or more sources are activated to generate acoustic energy that is reflected from the subterranean formation and recorded as pressure data by pressure sensors located in one or more streamers, the specific improvement comprising:

computing an approximate frozen free-surface profile of a free surface above a streamer based on pressure data generated by pressure sensors located at receiver locations along the streamer, the pressure data represents the measured pressure wavefield;

computing reflectivity and normal derivative of the reflectivity at the receiver locations based on the approximate frozen free-surface profile;

computing a normal derivative of the measured pressure wavefield at the receiver locations based on the reflectivity and the normal derivative of the reflectivity at the receiver locations;

computing an approximate normal-velocity wavefield at the receiver locations along the streamer based on the normal derivative of the measured pressure wavefield at the receiver locations, the approximate normal-velocity wavefield does not include low-frequency, streamer vibrational noise; and

generating an image of the subterranean formation based at least in part on the measured pressure wavefield and the approximate normal-velocity wavefield.

2. The process of claim 1, wherein computing the approximate frozen free-surface profile further comprises:

transforming pressure data from space-time domain to frequency-wavenumber domain;

for each trial depth of a series of trial depths,

computing forward and backward extrapolated gathers based on the pressure data,

transforming forward and backward extrapolated gathers from the frequency-wavenumber domain to the space-time domain;

computing a difference gather from forward and backward extrapolated gathers;

computing a set of maximum energy differences for a series of time windows applied to the difference gather; and

computing a profile of the approximate frozen free surface.

3. The process of claim 2, wherein computing the set of maximum energy differences for the series of time windows further comprises:

for each time window,

determining amplitude differences in the time window;

computing energy difference for each amplitude difference in the time window; and

determining a maximum energy differences from the energy differences in the time window.

4. The process of claim 2, wherein computing the profile of the approximate frozen free surface further comprises:

for each time window and for each trial depth, determining peak coordinates associated maximum energy difference in each of set of maximum energy differences;

determining receiver in-line and cross-line coordinates of receiver locations associated with the peak coordinates; and

computing interpolated frozen free-surface profile based on peak coordinates and associated in-line and cross-line coordinates, the interpolated frozen free-surface profile is the approximate frozen free-surface profile.

5. The process of claim 4, further comprising extending the approximate frozen free-surface profile beyond first and last receiver locations of the streamer.

6. The process of claim 1, wherein computing the reflectivity and normal derivative of reflectivity further comprises:

computing a unit normal vector of the approximate frozen free-surface profile;

computing reflectivity of the approximate frozen free-surface profile based on the unit normal vector at points along the approximate frozen free-surface profile;

computing reflectivity at the receiver coordinates based on the reflectivity of the approximate frozen free-surface profile; and

computing normal derivative of the reflectivity at the receiver coordinates.

7. The process of claim 1, wherein computing a normal derivative of the pressure wavefield at receiver locations further comprises:

compute elements of a monopole matrix based on the reflectivity;

compute elements of a dipole matrix based on the normal derivative of the reflectivity; and

compute derivative of the pressure wavefield at the receiver locations based on the monopole matrix and the dipole matrix.

8. The process of claim 1, further comprising computing an approximate vertical-velocity wavefield at receiver locations based on the normal-velocity wavefield at receiver locations and orientation of the receivers.

9. The process of claim 8, further comprising computing a combined vertical-velocity wavefield composed of the approximate vertical-velocity wavefield over a low-frequency range and a measured vertical-velocity wavefield for frequencies outside the low-frequency range.

10. The process of claim 8, further comprising computing an up-going pressure wavefield based on the approximate vertical-velocity wavefield and the measured pressure wavefield.

11. The process of claim 1, wherein the approximate normal-velocity wavefield and measured pressure wavefield are geophysical data products, further comprising recording the geophysical data product on a physical, non-volatile computer-readable medium suitable for importing onshore.

12. The process of claim 10, further comprising performing geophysical analysis onshore on the geophysical data product.

13. The process of claim 1, further comprising the measured pressure wavefield generated by one or more receivers located along the streamer.

14. A computer system for generating an image of a subterranean formation, the system comprising:

one or more processors;

one or more data-storage devices; and

machine-readable instructions stored in one or more of data-storage devices and executed by the one or more processors, the machine-readable instructions directed to

computing an approximate frozen free-surface profile of a free surface above a streamer based on pressure data generated by pressure sensors located at receiver locations along the streamer, the pressure data represents the measured pressure wavefield;

computing reflectivity and normal derivative of the reflectivity at the receiver locations based on the approximate frozen free-surface profile;

computing a normal derivative of the measured pressure wavefield at the receiver locations based on the reflectivity and the normal derivative of the reflectivity at the receiver locations;

computing an approximate normal-velocity wavefield at the receiver locations along the streamer based on the normal derivative of the measured pressure wavefield at the receiver locations, the approximate normal-velocity wavefield does not include low-frequency streamer vibrational noise; and

generating an image of the subterranean formation based at least in part on the measured pressure wavefield and the approximate normal-velocity wavefield.

15. The system of claim 14, wherein computing the approximate frozen free-surface profile further comprises:

transforming pressure data from space-time domain to frequency-wavenumber domain;

for each trial depth of a series of trial depths,

computing forward and backward extrapolated gathers based on the pressure data,

transforming forward and backward extrapolated gathers from the frequency-wavenumber domain to the space-time domain;

computing a difference gather from forward and backward extrapolated gathers;

computing a set of maximum energy differences for a series of time windows applied to the difference gather; and

computing a profile of the approximate frozen free surface.

16. The system of claim 15, wherein computing the set of maximum energy differences for the series of time windows further comprises:

for each time window,

determining amplitude differences in the time window;

computing energy difference for each amplitude difference in the time window; and

determining a maximum energy differences from the energy differences in the time window.

17. The system of claim 15, wherein computing the profile of the approximate frozen free surface further comprises:

for each time window and for each trial depth, determining peak coordinates associated maximum energy difference in each of set of maximum energy differences;

determining receiver in-line and cross-line coordinates of receiver locations associated with the peak coordinates; and

computing interpolated frozen free-surface profile based on peak coordinates and associated in-line and cross-line coordinates, the interpolated frozen free-surface profile is the approximate frozen free-surface profile.

18. The system of claim 17, further comprising extending the approximate frozen free-surface profile beyond first and last receiver locations of the streamer.

19. The system of claim 14, wherein computing the reflectivity and normal derivative of reflectivity further comprises:

computing a unit normal vector of the approximate frozen free-surface profile;

computing reflectivity of the approximate frozen free-surface profile based on the unit normal vector at points along the approximate frozen free-surface profile;

computing reflectivity at the receiver coordinates based on the reflectivity of the approximate frozen free-surface profile; and

computing normal derivative of the reflectivity at the receiver coordinates.

20. The system of claim 14, wherein computing a normal derivative of the pressure wavefield at receiver locations further comprises:

compute elements of a monopole matrix based on the reflectivity;

compute elements of a dipole matrix based on the normal derivative of the reflectivity; and

compute derivative of the pressure wavefield at the receiver locations based on the monopole matrix and the dipole matrix.

21. The system of claim 14, further comprising computing an approximate vertical-velocity wavefield at receiver locations based on the normal-velocity wavefield at receiver locations and orientation of the receivers.

22. A non-transitory computer-readable medium having machine-readable instructions encoded thereon for generating an image of a subterranean formation and enabling one or more processors of a computer system to perform the operations of

computing an approximate frozen free-surface profile of a free surface above a streamer based on pressure data generated by pressure sensors located at receiver locations along the streamer, the pressure data represents the measured pressure wavefield;

computing reflectivity and normal derivative of the reflectivity at the receiver locations based on the approximate frozen free-surface profile;

computing a normal derivative of the measured pressure wavefield at the receiver locations based on the reflectivity and the normal derivative of the reflectivity at the receiver locations;

computing an approximate normal-velocity wavefield at the receiver locations along the streamer based on the normal derivative of the measured pressure wavefield at the receiver locations, the approximate normal-velocity wavefield does not include low-frequency, streamer vibrational noise; and

generating an image of the subterranean formation based at least in part on the measured pressure wavefield and the approximate normal-velocity wavefield.

23. The medium of claim 22, wherein computing the approximate frozen free-surface profile further comprises:

transforming pressure data from space-time domain to frequency-wavenumber domain;

for each trial depth of a series of trial depths,

computing forward and backward extrapolated gathers based on the pressure data,

transforming forward and backward extrapolated gathers from the frequency-wavenumber domain to the space-time domain;

computing a difference gather from forward and backward extrapolated gathers;

computing a set of maximum energy differences for a series of time windows applied to the difference gather; and

computing a profile of the approximate frozen free surface.

24. The medium of claim 23, wherein computing the set of maximum energy differences for the series of time windows further comprises:

for each time window,

determining amplitude differences in the time window;

computing energy difference for each amplitude difference in the time window; and

determining a maximum energy differences from the energy differences in the time window.

25. The medium of claim 23, wherein computing the profile of the approximate frozen free surface further comprises:

for each time window and for each trial depth, determining peak coordinates associated maximum energy difference in each of set of maximum energy differences;

determining receiver in-line and cross-line coordinates of receiver locations associated with the peak coordinates; and

compute interpolated frozen free-surface profile based on peak coordinates and associated in-line and cross-line coordinates, the interpolated frozen free-surface profile is the approximate frozen free-surface profile.

26. The medium of claim 25, further comprising extending the approximate frozen free-surface profile beyond first and last receiver locations of the streamer.

27. The medium of claim 22, wherein computing the reflectivity and normal derivative of the reflectivity further comprises:

computing a unit normal vector of the approximate frozen free-surface profile;

computing reflectivity of the approximate frozen free-surface profile based on the unit normal vector at points along the approximate frozen free-surface profile;

computing reflectivity at the receiver coordinates based on the reflectivity of the approximate frozen free-surface profile; and

computing normal derivative of the reflectivity at the receiver coordinates.

28. The medium of claim 21, wherein computing a normal derivative of the pressure wavefield at receiver locations further comprises:

compute elements of a monopole matrix based on the reflectivity;

compute elements of a dipole matrix based on the normal derivative of the reflectivity; and

compute derivative of the pressure wavefield at the receiver locations based on the monopole matrix and the dipole matrix.

29. The medium of claim 22, further comprising computing an approximate vertical-velocity wavefield at receiver locations based on the normal-velocity wavefield at receiver locations and orientation of the receivers.