

CLAIMS

1. A method to determine structural information about a geological subsurface, the method comprising:
 - 5 using a programmable computer to perform the following:
 - separating dual-sensor seismic data into aliased and unaliased parts in a frequency-wavenumber domain;
 - processing the seismic data in the unaliased part using a conventional vertical wavenumber;
 - 10 processing the seismic data in the aliased part using an alternative vertical wavenumber additionally based on a Nyquist wavenumber for the seismic data;
 - combining the processed unaliased seismic data and the processed aliased seismic data; and
 - 15 generating an image of the geological subsurface using at least in part the combined processed unaliased and aliased seismic data, the image revealing structural information about the geological subsurface.
2. The method of claim 1, wherein the separating dual-sensor seismic data into
20 aliased and unaliased parts comprises:
 - imposing a free surface condition on the unaliased part of the seismic data using a conventional vertical wavenumber; and
 - imposing a free surface condition on the aliased part of the seismic data using
the an alternative vertical wavenumber.
- 25 3. The method of claim 2, wherein the conventional vertical wavenumber k_{z0} comprises:

$$k_{z0} = \sqrt{\left(\frac{\omega}{c}\right)^2 - k_x^2 - k_y^2}$$

and the alternative vertical wavenumber k_{zI} comprises:

$$k_{zI} = \sqrt{\left(\frac{\omega}{c}\right)^2 - (2k_{Ny-x} - |k_x|)^2 - (2k_{Ny-y} - |k_y|)^2},$$

where ω is circular frequency, c is speed of sound in water, k_x and k_y are orthogonal horizontal wavenumbers, and k_{Ny-x} and k_{Ny-y} are Nyquist wavenumbers in the inline and crossline directions, respectively for the seismic data.

4. The method of claim 2, wherein the conventional vertical wavenumber k_{z0} comprises:

$$k_{z0} = \sqrt{\left(\frac{\omega}{c}\right)^2 - k_x^2 - k_y^2}$$

10 and the alternative vertical wavenumber k_{zI} comprises:

$$k_{zI} = \sqrt{\left(\frac{\omega}{c}\right)^2 - (2k_{Ny-x} + k_x)^2 - (2k_{Ny-y} + k_y)^2},$$

where ω is circular frequency, c is speed of sound in water, k_x and k_y are orthogonal horizontal wavenumbers, and k_{Ny-x} and k_{Ny-y} are Nyquist wavenumbers in the inline and crossline directions, respectively for the seismic data.

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5. The method of claim 2, wherein the conventional vertical wavenumber k_{z0} comprises:

$$k_{z0} = \sqrt{\left(\frac{\omega}{c}\right)^2 - k_x^2}$$

and the alternative vertical wavenumber k_{zI} comprises:

$$20 \quad k_{zI} = \sqrt{\left(\frac{\omega}{c}\right)^2 - (2k_{Ny} - |k_x|)^2},$$

where ω is circular frequency, c is speed of sound in water, k_x is horizontal wavenumber, and k_{Ny} is Nyquist wavenumber for the seismic data.

6. The method of claim 2, wherein the conventional vertical wavenumber k_{z0} comprises:

$$k_{z0} = \sqrt{\left(\frac{\omega}{c}\right)^2 - k_x^2}$$

5 and the alternative vertical wavenumber k_{z1} comprises:

$$k_{z1} = \sqrt{\left(\frac{\omega}{c}\right)^2 - (2k_{Ny} + k_x)^2},$$

where ω is circular frequency, c is speed of sound in water, k_x is horizontal wavenumber, and k_{Ny} is Nyquist wavenumber for the seismic data.

10 7. The method of claim 2, wherein the separating the dual-sensor seismic data into aliased and unaliased portions of a frequency-wavenumber domain comprises applying the following equation:

$$\begin{pmatrix} P_0 \\ P_1 \\ \tilde{V}_0 \\ \tilde{V}_1 \end{pmatrix} = \frac{1}{D} \begin{pmatrix} k_{z1} \sin(k_{z0} z_R) \cos(k_{z1} z_R) & -\sin(k_{z0} z_R) \sin(k_{z1} z_R) \\ -k_{z0} \cos(k_{z0} z_R) \sin(k_{z1} z_R) & \sin(k_{z0} z_R) \sin(k_{z1} z_R) \\ k_{z0} k_{z1} \cos(k_{z0} z_R) \cos(k_{z1} z_R) & -k_{z0} \cos(k_{z0} z_R) \sin(k_{z1} z_R) \\ -k_{z0} k_{z1} \cos(k_{z0} z_R) \cos(k_{z1} z_R) & k_{z1} \sin(k_{z0} z_R) \cos(k_{z1} z_R) \end{pmatrix} \begin{pmatrix} P \\ \tilde{V} \end{pmatrix},$$

15 where P_0 and P_1 are an unaliased part and an aliased part, respectively, of recorded pressure P , $\tilde{V}_0$, and $\tilde{V}_1$ are a transformed unaliased part and a transformed aliased part, respectively, of transformed vertical particle velocity $\tilde{V} = -i\omega\rho V$, V is vertical particle velocity, ρ is water density, k_{z0} is the conventional vertical wavenumber, k_{z1} is the alternative vertical wavenumber, z_R is receiver depth, and denominator factor D is given by:

$$20 \quad D = k_{z1} \sin(k_{z0} z_R) \cos(k_{z1} z_R) - k_{z0} \cos(k_{z0} z_R) \sin(k_{z1} z_R).$$

8. The method of claim 1, wherein the separating the dual-sensor seismic data into aliased and unaliased portions of a frequency-wavenumber domain further comprises

incorporating a correction factor to account for differences in receiver array geometry for the dual sensors.

9. The method of claim 8, wherein the separating the dual-sensor seismic data into
 5 aliased and unaliased portions of a frequency-wavenumber domain comprises applying the following equation:

$$\begin{pmatrix} P_0 \\ P_1 \\ \tilde{V}_0 \\ \tilde{V}_1 \end{pmatrix} = \frac{1}{D'} \begin{pmatrix} k_{z1} \sin(k_{z0} z_R) \cos(k_{z1} z_R) & -F_c \sin(k_{z0} z_R) \sin(k_{z1} z_R) \\ -F_c k_{z0} \cos(k_{z0} z_R) \sin(k_{z1} z_R) & F_c \sin(k_{z0} z_R) \sin(k_{z1} z_R) \\ k_{z0} k_{z1} \cos(k_{z0} z_R) \cos(k_{z1} z_R) & -F_c k_{z0} \cos(k_{z0} z_R) \sin(k_{z1} z_R) \\ -F_c k_{z0} k_{z1} \cos(k_{z0} z_R) \cos(k_{z1} z_R) & F_c k_{z1} \sin(k_{z0} z_R) \cos(k_{z1} z_R) \end{pmatrix} \begin{pmatrix} P \\ \tilde{V} \end{pmatrix},$$

- where P_0 and P_1 are an unaliased part and an aliased part, respectively, of recorded pressure P , $\tilde{V}_0$, and $\tilde{V}_1$ are a transformed unaliased part and a transformed aliased part,
 10 respectively, of transformed vertical particle velocity $\tilde{V} = -i\omega\rho V$, V is vertical particle velocity, ρ is water density, k_{z0} is the conventional vertical wavenumber, k_{z1} is the alternative vertical wavenumber, z_R is receiver depth, denominator factor D' is given by:

$$D' = k_{z1} \sin(k_{z0} z_R) \cos(k_{z1} z_R) - F_c k_{z0} \cos(k_{z0} z_R) \sin(k_{z1} z_R),$$

and the correction factor F_c is given by:

$$15 \quad F_c = \frac{\sin\left[\frac{N_p \Delta x_p (2k_{Ny-x} - |k_x|)}{2}\right] \sin\left[\frac{\Delta x_v (2k_{Ny-x} - |k_x|)}{2}\right] \sin\left[\frac{N_v \Delta x_v k_x}{2}\right] \sin\left[\frac{\Delta x_p k_x}{2}\right]}{\sin\left[\frac{N_v \Delta x_v (2k_{Ny-x} - |k_x|)}{2}\right] \sin\left[\frac{\Delta x_p (2k_{Ny-x} - |k_x|)}{2}\right] \sin\left[\frac{N_p \Delta x_p k_x}{2}\right] \sin\left[\frac{\Delta x_v k_x}{2}\right]}$$

where N_p and N_v are numbers of pressure and velocity sensors, respectively; Δx_p and Δx_v , are pressure and velocity sensor spacing, respectively, k_{Ny-x} is Nyquist wavenumber in the inline direction; and k_x is horizontal wavenumber.

- 20 10. At least one computer readable medium with a computer program stored thereon, the program having logic operable to cause at least one programmable computer to

perform a method that determines structural information about a geological subsurface, the method comprising:

separating dual-sensor seismic data into aliased and unaliased parts in a frequency-wavenumber domain;

5 processing the seismic data in the unaliased part using a conventional vertical wavenumber;

processing the seismic data in the aliased part using an alternative vertical wavenumber additionally based on a Nyquist wavenumber for the seismic data;

combining the processed unaliased seismic data and the processed aliased seismic data; and

generating an image of the geological subsurface using at least in part the combined processed unaliased and aliased seismic data, the image revealing structural information about the geological subsurface.

15 11. The medium of claim 10, wherein the separating dual-sensor seismic data into aliased and unaliased parts comprises:

imposing a free surface condition on the unaliased part of the seismic data using a conventional vertical wavenumber; and

imposing a free surface condition on the aliased part of the seismic data using the an alternative vertical wavenumber.

12. The medium of claim 11, wherein the conventional vertical wavenumber k_{z0} comprises:

$$k_{z0} = \sqrt{\left(\frac{\omega}{c}\right)^2 - k_x^2 - k_y^2}$$

25 and the alternative vertical wavenumber k_{z1} comprises:

$$k_{z1} = \sqrt{\left(\frac{\omega}{c}\right)^2 - (2k_{Ny-x} - |k_x|)^2 - (2k_{Ny-x} - |k_y|)^2},$$

where ω is circular frequency, c is speed of sound in water, k_x and k_y are orthogonal horizontal wavenumbers, and k_{Ny-x} and k_{Ny-y} are Nyquist wavenumbers in the inline and crossline directions, respectively for the seismic data.

- 5 13. The medium of claim 11, wherein the conventional vertical wavenumber k_{z0} comprises:

$$k_{z0} = \sqrt{\left(\frac{\omega}{c}\right)^2 - k_x^2 - k_y^2}$$

and the alternative vertical wavenumber k_{z1} comprises:

$$k_{z1} = \sqrt{\left(\frac{\omega}{c}\right)^2 - (2k_{Ny-x} + k_x)^2 - (2k_{Ny-y} + k_y)^2},$$

- 10 where ω is circular frequency, c is speed of sound in water, k_x and k_y are orthogonal horizontal wavenumbers, and k_{Ny-x} and k_{Ny-y} are Nyquist wavenumbers in the inline and crossline directions, respectively for the seismic data.

14. The medium of claim 11, wherein the conventional vertical wavenumber k_{z0}
15 comprises:

$$k_{z0} = \sqrt{\left(\frac{\omega}{c}\right)^2 - k_x^2}$$

and the alternative vertical wavenumber k_{z1} comprises:

$$k_{z1} = \sqrt{\left(\frac{\omega}{c}\right)^2 - (2k_{Ny} - |k_x|)^2},$$

- where ω is circular frequency, c is speed of sound in water, k_x is horizontal wavenumber,
20 and k_{Ny} is Nyquist wavenumber for the seismic data.

15. The medium of claim 11, wherein the conventional vertical wavenumber k_{z0} comprises:

$$k_{z0} = \sqrt{\left(\frac{\omega}{c}\right)^2 - k_x^2}$$

and the alternative vertical wavenumber k_{z1} comprises:

$$k_{z1} = \sqrt{\left(\frac{\omega}{c}\right)^2 - (2k_{Ny} + k_x)^2},$$

where ω is circular frequency, c is speed of sound in water, k_x is horizontal wavenumber,

5 and k_{Ny} is Nyquist wavenumber for the seismic data.

16. The medium of claim 11, wherein the separating the dual-sensor seismic data into aliased and unaliased portions of a frequency-wavenumber domain comprises applying the following equation:

$$10 \quad \begin{pmatrix} P_0 \\ P_1 \\ \tilde{V}_0 \\ \tilde{V}_1 \end{pmatrix} = \frac{1}{D} \begin{pmatrix} k_{z1} \sin(k_{z0} z_R) \cos(k_{z1} z_R) & -\sin(k_{z0} z_R) \sin(k_{z1} z_R) \\ -k_{z0} \cos(k_{z0} z_R) \sin(k_{z1} z_R) & \sin(k_{z0} z_R) \sin(k_{z1} z_R) \\ k_{z0} k_{z1} \cos(k_{z0} z_R) \cos(k_{z1} z_R) & -k_{z0} \cos(k_{z0} z_R) \sin(k_{z1} z_R) \\ -k_{z0} k_{z1} \cos(k_{z0} z_R) \cos(k_{z1} z_R) & k_{z1} \sin(k_{z0} z_R) \cos(k_{z1} z_R) \end{pmatrix} \begin{pmatrix} P \\ \tilde{V} \end{pmatrix},$$

where P_0 and P_1 are an unaliased part and an aliased part, respectively, of recorded pressure P , $\tilde{V}_0$, and $\tilde{V}_1$ are a transformed unaliased part and a transformed aliased part, respectively, of transformed vertical particle velocity $\tilde{V} = -i\omega\rho V$, V is vertical particle velocity, ρ is water density, k_{z0} is the conventional vertical wavenumber, k_{z1} is the alternative vertical wavenumber, z_R is receiver depth, and denominator factor D is given by:

$$D = k_{z1} \sin(k_{z0} z_R) \cos(k_{z1} z_R) - k_{z0} \cos(k_{z0} z_R) \sin(k_{z1} z_R).$$

17. The medium of claim 10, wherein the separating the dual-sensor seismic data into aliased and unaliased portions of a frequency-wavenumber domain further comprises

incorporating a correction factor to account for differences in receiver array geometry for the dual sensors.

18. The medium of claim 17, wherein the separating the dual-sensor seismic data into aliased and unaliased portions of a frequency-wavenumber domain comprises applying the following equation:

$$5 \quad \begin{pmatrix} P_0 \\ P_1 \\ \tilde{V}_0 \\ \tilde{V}_1 \end{pmatrix} = \frac{1}{D'} \begin{pmatrix} k_{z1} \sin(k_{z0} z_R) \cos(k_{z1} z_R) & -F_c \sin(k_{z0} z_R) \sin(k_{z1} z_R) \\ -F_c k_{z0} \cos(k_{z0} z_R) \sin(k_{z1} z_R) & F_c \sin(k_{z0} z_R) \sin(k_{z1} z_R) \\ k_{z0} k_{z1} \cos(k_{z0} z_R) \cos(k_{z1} z_R) & -F_c k_{z0} \cos(k_{z0} z_R) \sin(k_{z1} z_R) \\ -F_c k_{z0} k_{z1} \cos(k_{z0} z_R) \cos(k_{z1} z_R) & F_c k_{z1} \sin(k_{z0} z_R) \cos(k_{z1} z_R) \end{pmatrix} \begin{pmatrix} P \\ \tilde{V} \end{pmatrix},$$

where P_0 and P_1 are an unaliased part and an aliased part, respectively, of recorded pressure P , $\tilde{V}_0$, and $\tilde{V}_1$ are a transformed unaliased part and a transformed aliased part, respectively, of transformed vertical particle velocity $\tilde{V} = -i\omega\rho V$, V is vertical particle velocity, ρ is water density, k_{z0} is the conventional vertical wavenumber, k_{z1} is the alternative vertical wavenumber, z_R is receiver depth, denominator factor D' is given by:

$$D' = k_{z1} \sin(k_{z0} z_R) \cos(k_{z1} z_R) - F_c k_{z0} \cos(k_{z0} z_R) \sin(k_{z1} z_R),$$

and the correction factor F_c is given by:

$$F_c = \frac{\sin\left[\frac{N_p \Delta x_p (2k_{Ny-x} - |k_x|)}{2}\right] \sin\left[\frac{\Delta x_v (2k_{Ny-x} - |k_x|)}{2}\right] \sin\left[\frac{N_v \Delta x_v k_x}{2}\right] \sin\left[\frac{\Delta x_p k_x}{2}\right]}{\sin\left[\frac{N_v \Delta x_v (2k_{Ny-x} - |k_x|)}{2}\right] \sin\left[\frac{\Delta x_p (2k_{Ny-x} - |k_x|)}{2}\right] \sin\left[\frac{N_p \Delta x_p k_x}{2}\right] \sin\left[\frac{\Delta x_v k_x}{2}\right]}$$

where N_p and N_v are numbers of pressure and velocity sensors, respectively; Δx_p and Δx_v , are pressure and velocity sensor spacing, respectively, k_{Ny-x} is Nyquist wavenumber in the inline direction; and k_x is horizontal wavenumber.