

### CLAIMS

1. A ray-based  $Q$ -tomography method using recorded reflection seismic data from a subsurface region, comprising migrating the seismic data to depth domain to obtain common image gathers, said common image gathers being common offset gathers, where a kernel matrix is constructed using raypath information obtained through a ray tracing procedure, and selected seismic traces from a common image gather are converted to time domain, then a centroid frequency shift relative to a seismic source wavelet centroid frequency is determined, then an expression relating the centroid frequency shift and the kernel matrix to seismic attenuation, as measured by a frequency independent quality factor  $Q$ , is iteratively solved for  $Q$  using a computer.
2. The method of claim 1, wherein the kernel matrix construction comprises:
- (a) in each image corresponding to a common offset, selecting at least one horizon, and on the horizon at least one common depth point;
  - (b) tracing two rays from each selected common depth point to the surface;
  - (c) measuring ray lengths in each penetrated subsurface grid, each subsurface grid corresponding to a column index of the kernel matrix, and using a subsurface velocity model to form elements of the kernel matrix.
3. The method of claim 2, wherein (b) comprises:
- (i) estimating a dip angle of the selected horizon where the selected common depth point is located;
  - (ii) finding two takeoff directions making equal angles with the normal direction to the horizon at the selected common depth point such that two rays traced using Snell's Law from the selected common depth point at the two takeoff directions reach surface locations that are separated by the common offset;
  - (iii) tracing the two rays defined in (ii).
4. The method of claim 3, wherein (ii) comprises:

deploying a plurality of virtual sources on the surface;

performing wavefront construction based ray tracing from the virtual sources to the selected common depth point and building a table giving ray incident angle at the selected common depth point for each virtual source location; and

5        selecting from the table two incident angles for the selected common depth point that match the common offset, and using these two selected incident angles as the takeoff directions.

5.        The method of claim 1, wherein:

10        the selected seismic traces comprise a vertical trace for each selected common depth point, extracted from the common image gather;

the conversion to time domain of the selected seismic traces is performed while applying a wavelet stretching correction; and

15        the centroid frequency shift is determined for each selected trace after transforming the selected trace to frequency domain.

6.        The method of claim 5, wherein the conversion to time domain and the wavelet stretching correction, can be expressed by

$$\Delta t(z) = \frac{\Delta z(z)}{v(z)} [\cos(\theta_i + \theta_d) + \cos(\theta_i - \theta_d)]$$

20        where  $\Delta t$  is a time duration corresponding to  $\Delta z$ , which is proportional to vertical mesh size in a computational grid, as a function of depth  $z$ ;  $v(z)$  is vertical seismic velocity profile as a function of the depth  $z$ ;  $\theta_i$  is seismic ray incident angle at the selected common depth point; and  $\theta_d$  is dip angle of the selected horizon at the selected common depth point.

7.        The method of claim 5, wherein the determination of the centroid frequency shift  
25        comprises analyzing the source wavelet frequency distribution and fitting an asymmetric frequency distribution with a frequency weighted exponential function of frequency, and further comprising computing a component of a measurement vector from the centroid frequency shift and using the measurement vector to represent the centroid frequency shift in

the expression that is solved by iterative optimization.

8. The method of claim 7, wherein the frequency-weighted exponential function of frequency can be expressed in the form

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$$F(f) = Af^n \exp\left(-\frac{f}{f_0}\right)$$

where  $f$  is frequency,  $A$  is a constant for amplitude scaling,  $f_0$  is a characteristic frequency, and  $n$  is a symmetry index.

9. The method of claim 5, wherein the extracted vertical traces are truncated to include  
10 only the events associated with the selected horizon.

10. The method of claim 1, wherein the iterative solving for  $Q$  comprises a linear optimization using box constraints to keep estimated  $Q$  values within position-dependent ranges specified by upper boundaries and lower boundaries.

15 11. The method of claim 1, wherein the iterative solving for  $Q$  comprises a constrained optimization that is solved by a multi-index active-set method that allows updates of the active set by multiple computational grid indices at a time, wherein a grid index denotes subsurface location.

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## CLAIMS

1. A ray-based Q-tomography method using recorded reflection seismic data from a subsurface region, comprising migrating the seismic data to depth domain to obtain common image gathers, said common image gathers being common offset gathers, where a kernel matrix is constructed using raypath information obtained through a ray tracing procedure, wherein the kernel matrix construction comprises:

(a) in each image corresponding to a common offset, selecting at least one horizon, and on the horizon at least one common depth point;

(b) tracing two rays from each selected common depth point to the surface; by

(i) estimating a dip angle of the selected horizon where the selected common depth point is located;

(ii) finding two takeoff directions making equal angles with the normal direction to the horizon at the selected common depth point such that two rays traced using Snell's Law from the selected common depth point at the two takeoff directions reach surface locations that are separated by the common offset; and

(iii) tracing the two rays defined in (ii);

(c) measuring ray lengths in each penetrated subsurface grid, each subsurface grid corresponding to a column index of the kernel matrix, and using a subsurface velocity model to form elements of the kernel matrix;

and selected seismic traces from a common image gather are converted to time domain, then a centroid frequency shift relative to a seismic source wavelet centroid frequency is determined, then an expression relating the centroid frequency shift and the kernel matrix to seismic attenuation, as measured by a frequency independent quality factor  $Q$ , is iteratively solved for  $Q$  using a computer.

2. The method of claim 1, wherein (ii) comprises:

deploying a plurality of virtual sources on the surface;

performing wavefront construction based ray tracing from the virtual sources to the selected common depth point and building a table giving ray incident angle at the selected common depth point for each virtual source location; and

selecting from the table two incident angles for the selected common depth point that match the common offset, and using these two selected incident angles as the takeoff directions.

3. The method of claim 1, wherein:

the selected seismic traces comprise a vertical trace for each selected common depth point, extracted from the common image gather;

the conversion to time domain of the selected seismic traces is performed while applying a wavelet stretching correction; and

the centroid frequency shift is determined for each selected trace after transforming the selected trace to frequency domain.

4. The method of claim 3, wherein the conversion to time domain and the wavelet stretching correction, can be expressed by

$$\Delta t(z) = \frac{\Delta z(z)}{v(z)} [\cos(\theta_i + \theta_d) + \cos(\theta_i - \theta_d)]$$

where  $\Delta t$  is a time duration corresponding to  $\Delta z$ , which is proportional to vertical mesh size in a computational grid, as a function of depth  $z$ ;  $v(z)$  is vertical seismic velocity profile as a function of the depth  $z$ ;  $\theta_i$  is seismic ray incident angle at the selected common depth point; and  $\theta_d$  is dip angle of the selected horizon at the selected common depth point.

5. The method of claim 3, wherein the determination of the centroid frequency shift comprises analyzing the source wavelet frequency distribution and fitting an asymmetric frequency distribution with a frequency weighted exponential function of frequency, and further comprising computing a component of a measurement vector from the centroid frequency shift and using the measurement vector to represent the centroid frequency shift in the expression that is solved by iterative optimization.

6. The method of claim 5, wherein the frequency-weighted exponential function of frequency can be expressed in the form

$$F(f) = Af^n \exp\left(-\frac{f}{f_0}\right)$$

where  $f$  is frequency,  $A$  is a constant for amplitude scaling,  $f_0$  is a characteristic frequency, and  $n$  is a symmetry index.

7. The method of claim 3, wherein the extracted vertical traces are truncated to include only the events associated with the selected horizon.

8. The method of claim 1, wherein the iterative solving for  $Q$  comprises a linear optimization using box constraints to keep estimated  $Q$  values within position-dependent ranges specified by upper boundaries and lower boundaries.

9. The method of claim 1, wherein the iterative solving for  $Q$  comprises a constrained optimization that is solved by a multi-index active-set method that allows updates of the active set by multiple computational grid indices at a time, wherein a grid index denotes subsurface location.