

CLAIMS

WHAT IS CLAIMED IS:

1. A method for seismic exploration, the method comprising:
5 using pressure changes caused by variations of a sea surface as a low-frequency seismic energy source with no active seismic energy source;
obtaining dual wave-fields measured below the sea surface;
selecting an observation level;
decomposing, by computer, the dual wave-fields into a down-going wave-field
10 and an up-going wave-field at the observation level; and
generating, by computer, seismic images using the down-going and up-going wave-fields.
2. The method of claim 1, wherein the low-frequency seismic energy source
15 includes wave energy at frequencies less than five hertz.
3. The method of claim 1, wherein the dual wave-field data is acquired at an acquisition surface that is distinct from the observation level~~an active seismic source is also used.~~

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4. The method of claim 1, wherein generating the seismic images comprises using the down-going wave-field as a source wave-field and using the up-going wave-field as a receiver wave-field.
- 5 5. The method of claim 4, wherein generating the seismic images comprises iteratively performing:
- stepwise propagation of the down-going source wave-field forward in time to a depth level;
- stepwise propagation of the up-going receiver wave-field backward in time to
- 10 the depth level; and
- applying a deconvolution imaging condition to the source and receiver wave-fields to obtain a reflectivity function at the depth level.
6. The method of claim 4, wherein generating the seismic images using the down-
- 15 going source and up-going receiver wave-fields comprises applying an imaging condition to the down-going source and the up-going receiver wave-fields to obtain seismic image data.
7. The method of claim 1, wherein a first wave-field of the dual wave-fields
- 20 comprises a pressure wave-field.

8. The method of claim 7, wherein a second wave-field of the dual wave-fields comprises a velocity wave-field.
9. The method of claim 8, wherein the pressure and velocity wave-fields are
5 recorded using a marine-towed dual-sensor streamer.
10. The method of claim 8, wherein the pressure and velocity wave-fields are recorded using an ocean bottom cable or node system.
- 10 11. The method of claim 7, wherein a second wave-field of the dual wave-fields comprises a pressure-derivative wave-field.
12. The method of claim 11, wherein the pressure and pressure-derivative wave-fields are recorded using a marine-towed over/under streamer.
- 15 13. ~~The method of claim 3, further comprising:~~
~~—determining a down-going source wave field and an up-going receiver wave-~~
~~field at higher frequencies on the observation level from the dual wave fields; and~~
~~—generating seismic images using the down-going source and up-going receiver~~
20 ~~wave fields at the higher frequencies;~~
~~—wherein a primary source for the wave fields at the higher frequencies comprises~~
~~an artificial underwater seismic energy source which generates an acoustic wave field.~~

1314. An apparatus configured to generate seismic images ~~using pressure changes caused by variations in a sea surface as a low-frequency seismic energy source~~, the apparatus comprising:

- 5 memory configured to store processor-executable code and data;
 at least one processor configured to execute said processor-executable code so as to modify said data;
 processor-executable code configured to obtain dual wave-fields measured
10 below the sea surface, wherein the dual wave-fields are caused by variations in a sea surface as a passive seismic source with no active seismic source;
 processor-executable code configured to select an observation level;
 processor-executable code configured to decompose the dual wave-fields into a down-going wave-field and an up-going wave-field at the observation level; and
 processor-executable code configured to generate seismic images using, at least
15 in part, low-frequency components of the down-going and up-going wave-fields.

1415. The apparatus of claim 1314, wherein the low-frequency components include frequencies less than five hertz, and wherein a primary source for the low-frequency components comprises pressure-variations of sea-surface waves.

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1516. The apparatus of claim 1314, wherein the processor-executable code configured to generate the seismic images uses the down-going wave-field as a source wave-field and the up-going wave-field as a receiver wave-field.

5 | 1617. The apparatus of claim 1516, further comprising:

processor-executable code configured to iteratively perform a) stepwise propagation of the down-going source wave-field forward in time to a depth level, b) stepwise propagation of the up-going receiver wave-field backward in time to the depth level, and c) applying a deconvolution imaging condition to the source and receiver
10 wave-fields to obtain a reflectivity function at the depth level.

| 1718. The apparatus of claim 1516, further comprising:

processor-executable code configured to correlate the down-going source and up-going receiver wave-fields to obtain seismic image data.

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| 1819. The apparatus of claim 1314, wherein a first wave-field of the dual wave-fields comprises a pressure wave-field, a second wave-field of the dual wave-fields comprises a velocity wave-field, and the pressure and velocity wave-fields are measured using a marine-towed dual-sensor streamer.

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| 1920. The apparatus of claim 1314, wherein a first wave-field of the dual wave-fields comprises a pressure wave-field, a second wave-field of the dual wave-fields comprises

a pressure-derivative wave-field, and the pressure and pressure-derivative wave-fields are measured using a marine-towed over/under streamer.

5 ~~2021.~~ The apparatus of claim ~~1345~~, wherein the dual wave-field data is acquired at an acquisition surface that is distinct from the observation level~~further comprising:~~

~~— processor-executable code configured to determine a down-going source wave-field and an up-going receiver wave-field at higher frequencies on the observation level from the dual wave-fields; and~~

10 ~~— processor-executable code configured to generate seismic images using the down-going source and up-going receiver wave-fields at the higher frequencies;~~

~~— wherein a primary source for the wave-fields at the higher frequencies comprises an artificial underwater seismic energy source which generates an acoustic wave-field.~~

15 ~~2122.~~ A marine seismic imaging system comprising:

 marine seismic wave-field acquisition apparatus configured to measure and record dual wave-field data caused by variations in a sea surface as a passive seismic source with no active seismic source; and

 data processing apparatus configured to generate seismic images from the dual wave-field data, the data processing apparatus including

20 memory configured to store processor-executable code and data,

 a processor configured to execute said processor-executable code so as to modify said data,

processor-executable code configured to decompose the dual wave-field data into a down-going source wave-field and an up-going receiver wave-field at a selected observation level; and

processor-executable code configured to generate seismic images using, at least
5 in part, low-frequency components of the down-going source and up-going receiver
wave-fields, ~~wherein an energy source for the low-frequency components comprises
sea-surface variations.~~

2223. The system of claim 2122, wherein the low-frequency components include
10 frequencies less than five hertz.

2324. The system of claim 2123, wherein the dual wave-field data is acquired at an
acquisition surface, and wherein the observation level is distinct from the acquisition
surface~~further comprising:~~
15 ~~an artificial underwater seismic energy source which generates an acoustic
wave-field.~~

2425. At least one tangible computer-readable storage medium with executable code
stored thereon which, when executed by one or more processors, performs steps
20 comprising:

obtaining dual wave-fields measured below a sea surface, wherein the dual wave-fields include low-frequency components whose energy source is passive and comprises variations of a sea surface with no active seismic energy source;

5 decomposing the dual wave-fields into a down-going wave-field and an up-going wave-field at an observation level; and

generating seismic images using the low-frequency components of the down-going source and up-going receiver wave-fields.