Imaging primaries and high-order multiples for permanent reservoir monitoring: Application to Jubarte field

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Abstract

A superior depth-migration solution that uses all the recorded data, including primaries and all orders of multiples, can be adapted from towed-streamer acquisition to ocean-bottom cable (OBC) or ocean-bottom node (OBN) acquisition. The technology has been validated using the 3D/4D data sets acquired by Petrobras for the deepwater Jubarte PRM pilot in Campos Basin. Images constructed from primaries and all orders of sea-surface reflections shows improved subsurface coverage when compared with images from primaries alone and/or mirror migration. The resulting 4D signal also shows a good match with the well trajectory, validating the use of this novel technology for 4D imaging studies.

Introduction

The use of permanent reservoir monitoring (PRM) installations has become increasingly common in the oil industry. The technology promises good data repeatability and quality, especially in the presence of obstacles that can prevent the use of conventional streamers. However, two drawbacks of PRM with ocean-bottom cables are the limited subsurface coverage associated with the cables and the large receiver separation at the sea bottom that delivers poor illumination for shallow targets.

The industry has found a processing solution to this problem by using mirror migration (Grion et al., 2007), which consists of separating the seabed hydrophone and geophone data into upgoing and downgoing wavefields. First-order multiples in the downgoing wavefield are then imaged by treating them as though they had been recorded above the sea surface at an elevation equal to the sea depth. This procedure generates better images than those produced conventionally from the upgoing primary wavefield because it expands the area of illumination for shallow targets. Nevertheless, the results from mirror migration can be improved further because it uses only first-order multiples in the downgoing wavefield to create an image.

A superior depth-migration solution that uses all the recorded data, including primaries and all orders of multiples (Berkhout and Verschuur, 1994; Whitmore et al., 2010), can be adapted from towed-streamer acquisition to ocean-bottom cable (OBC) or ocean-bottom node (OBN) acquisition. Using this technology, for a collaborative Petrobras/PGS technology project, we have imaged the seismic data from a deepwater PRM survey that Petrobras acquired over the Jubarte field in the Campos Basin. Images constructed from primaries and all orders of sea-surface reflections show improved subsurface coverage when compared with images from primaries alone and/or mirror migration. The improvements are not limited to image quality. The resulting 4D signal also shows a good match with the well trajectory, validating the use of this novel technology for 4D imaging studies.

Deepwater PRM context

Permanent reservoir monitoring installations can be considered the ultimate solution for detecting small seismic-signal variation related to reservoir production. Time-lapse seismic data are recorded, enabling analysis of the changes in terms of fluid saturation and pressure. Because the cables are deployed permanently on the seabed, the recording system ensures the best repeatability and provides effective operations for the different monitor survey acquisitions.

In 2012, Petrobras installed the first deepwater optical PRM system provided by PGS on the Jubarte field in the Campos Basin (Figure 1a). This pilot project covers ~ 10 km^2, with the primary objective being to validate the fiber-optic sensing technology in detecting subtle impedance changes in the reservoir. The layout of the 35-km optical cable was designed with the upgoing seismic wavefield in mind. The main challenge was to optimize the geometry of the seabed recording cable and the density of multicomponent receivers for ensuring sufficient illumination of the reservoir and effective 4D seismic detectability while avoiding any crossings of the existing subsea infrastructure (Thedy et al., 2013).

A total of 712 seismic recording stations distributed along two cables was deployed successfully in water depths varying from 1250 m to 1350 m. Receivers are positioned every 50 m along the cable, with the array consisting of 11 receiver lines separated by ~ 300 m (Figure 1b). A source grid covering an area of 11 km × 11 km was acquired, with source locations at intervals of 25 m × 25 m.

The first 4D signals have been observed after one year of reservoir production using the active seismic surveys completed in early 2013 and early 2014. The resulting monitoring image has

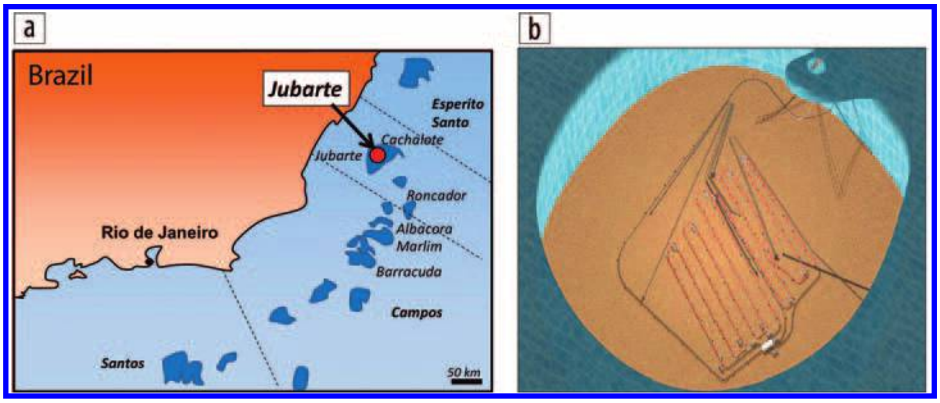

Figure 1. (a) Location of the Jubarte field in Campos Basin. (b) Layout of fiber-optic ocean-bottom cables.

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been limited to the area of ~ 10 km^2 but was sufficient for validating the deepwater pilot installation. The excellent 4D seismic results (Figure 2) demonstrate the high detectability expected from a permanent optical installation and confirm the value of extending the permanent seismic installation to the north and northwest, covering more of the Jubarte field.

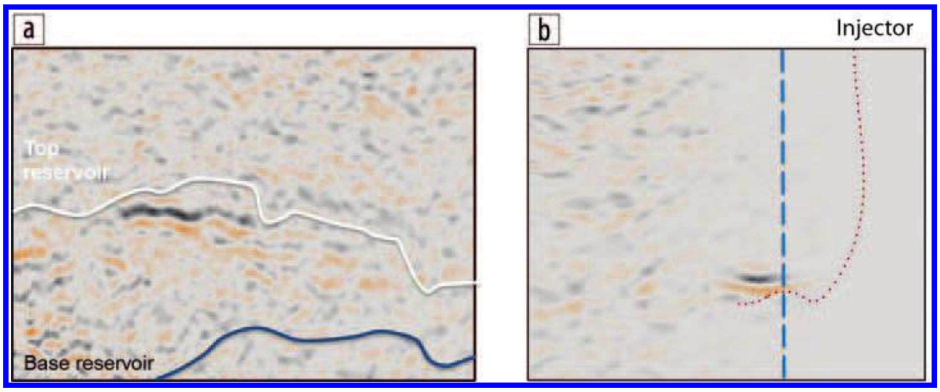

Figure 2. 4D signal results within two sail lines: (a) OWC changes; (b) water injection. Because the injector (red dotted line) is located at the edge of the recording system (vertical blue dashed line), only one part of the 4D signal (with "smiling" effect) is visible using the primary reflection imaging.

High-order imaging of multiples for seabed acquisition

The 4D Jubarte data sets were used for validating an original imaging solution that uses all the recorded data, primaries and all orders of multiples, for reservoir monitoring. This novel technology was adapted from a seismic-imaging technique developed for dual-sensor streamer acquisition (Whitmore et al., 2010). This imaging method makes use of both the upgoing and downgoing wavefields to produce seismic images from all orders of sea-surface reflections (Lu et al., 2015). The advantage of using the separated upgoing and downgoing wavefields is that in case of a marine streamer acquisition, it turns each receiver into a "virtual" source, increasing the spatial extent and quality of images, particularly for shallow targets.

The OBC processing sequence starts by separating the upgoing and downgoing wavefields from the seabed hydrophone and geophone data. The separation can be done using PZ-summation and PZ-subtraction processes. Later, the data are organized into receiver gathers. The resultant upgoing and downgoing wavefields are migrated independently for imaging geologic structures using the respective primary and all orders of sea-surface reflections. In the migration, the source and receiver wavefields are forward- and backward-extrapolated into the earth, and an image is constructed by applying a deconvolution imaging condition. The dense areal source carpet, which results from imaging with all orders of sea-surface reflections, expands the image of the subsurface. It expands the illumination significantly even when compared with mirror migration.

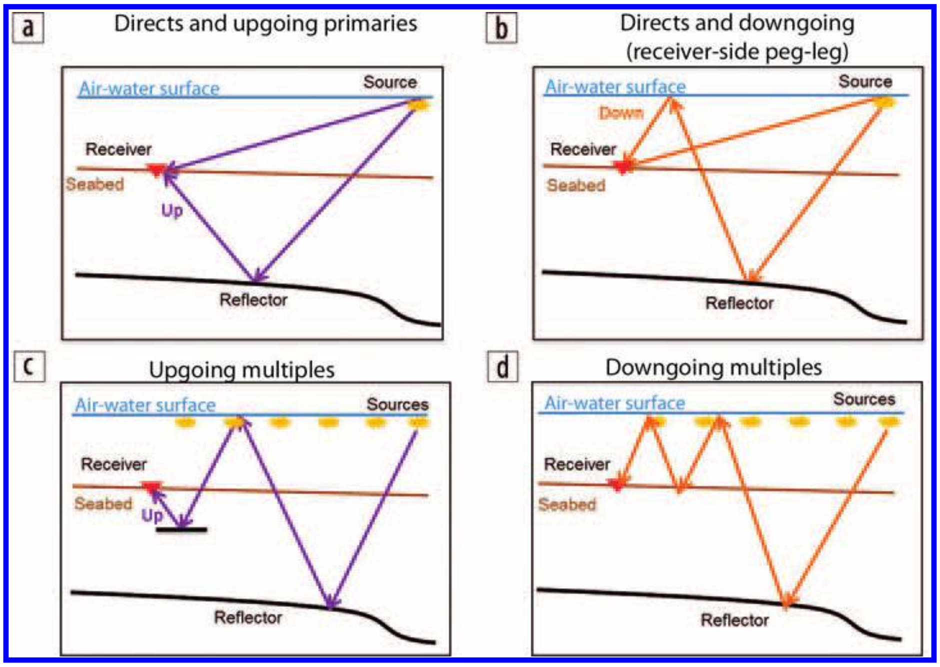

Figure 3. Schematics describing wavefields used by the new OBC imaging technology for imaging the reservoir. Conventional OBC imaging techniques use only the (a) upgoing or (b) downgoing wavefield. In contrast, imaging of surface multiples also can be facilitated by using (c) upgoing and (d) downgoing wavefields, with each receiver location acting as a virtual source.

Figure 3 describes examples of wavefields used for imaging the reservoir with seabed acquisition data sets. Conventional OBC imaging techniques use only the upgoing wavefield (Figure 3a) or the downgoing wavefield (Figure 3b). By exploiting all the data, including primaries and all orders of sea-surface reflections/multiples described in Figures 3c and 3d, the illuminated part of the reflector can be extended significantly. The number of orders of sea-surface reflections used in the imaging process is determined simply by the water depth and the record length.

This new technology has numerous advantages when compared with conventional seabed data processing:

1) Extending target illumination. Because every order of sea-surface reflection has different reflection points, the illumination area is extended significantly compared with conventional imaging that uses upgoing primary reflections only or mirror imaging that uses first-order receiver peg-leg only (downgoing). By transforming every shot pair into a virtual sea-surface source-receiver couple, the illuminated area essentially is defined by the surface distribution of the seismic source and the

maximum order of multiples recorded (Figure 4). Figure 5 shows the comparison between an image provided by conventional upgoing primary reflections and an image computed from all orders of multiples available in the upgoing wavefield. The circle delimits the reservoir target. It can be noticed that the upgoing primary reflection image is limited by the receiver array (~ 3 km × 3 km), whereas the image of all orders of multiples is defined by the source area (~ 11 km × 11 km).

2) Improving source repeatability. The imaging principle described here consists of a deconvolution imaging condition that provides a good estimate of the image reflectivity. It effectively removes the source signature and the bubble effect, resulting in a zero-phase image. This is especially appealing for 4D surveys in which repeating the seismic source between surveys is an important requirement.
3) Fast turnaround. Except for PZ-summation/subtraction, the preprocessing workflow does not include any demultiple process, which can be complex and "compute intensive." The imaging principle makes use of direct arrivals, primary as well as higher orders of sea-surface reflections included in the upgoing and downgoing wavefields.

Can multiples be used for 4D studies?

The technical validity for a reservoir monitoring system has to be demonstrated using a 4D signal related to the reservoir production. In the PRM pilot area, a water injector is located on the edge of the receiver array. Using the upgoing primary wavefield, conventional 4D processing detects the 4D signal only around the foot of the injector (Figure 2). The 4D signal clearly is limited by the illumination of the primary reflections. The challenge was to provide the continuity of the same 4D signal outside the receiver array using primaries and all orders of sea-surface reflections/multiples. In Figure 6, base and monitor images are displayed alongside the 4D difference at the water-injector level. Dashed lines represent the limit of the conventional upgoing 4D image.

The 4D signal extracted from the multiples imaging technique is clearly visible in Figure 6c. The image match with the well trajectory validates the use of high-order sea-surface reflections for 4D imaging studies.

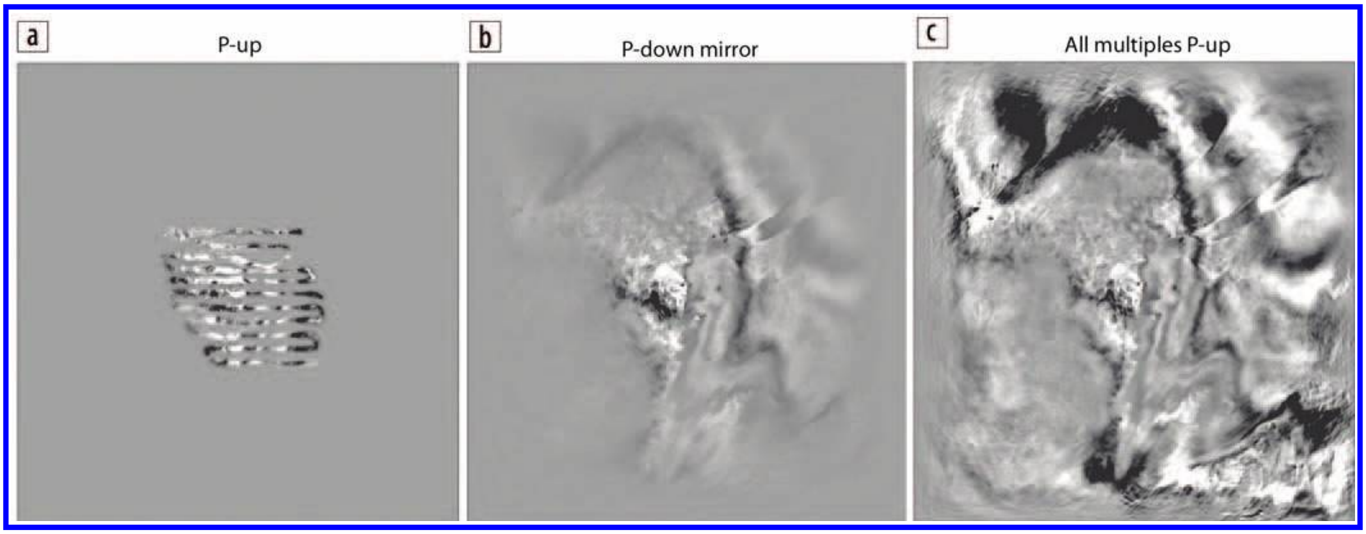

Figure 4. Depth imaging slices at the water-bottom level provided by (a) the upgoing primary reflection, (b) the downgoing primary reflection, and (c) all orders of mltiples included in the upgoing wavefield.

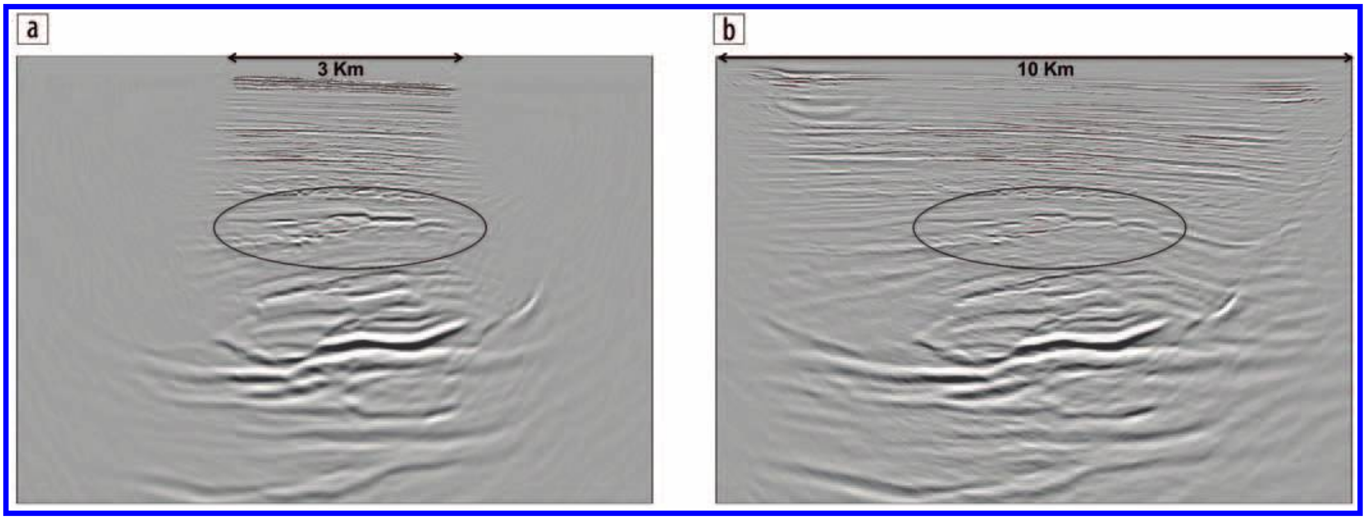

Figure 5. (a) Image provided by upgoing primary reflections. (b) Image provided by all orders of multiple included in the upgoing wavefield (refer to Figures 3a and 3c, respectively). The reservoir target is delimited by the circle. The image is extended significantly for all reflectors.

Conclusions

We have demonstrated that the imaging technique using all orders of sea-surface multiples is appropriate for seabed data sets in 3D and 4D contexts. The methodology offers numerous advantages over conventional seabed data processing; target illumination is extended significantly, source repeatability is improved, and the processing sequence is optimized by removing complex demultiple processes. The new imaging technology has been validated using Petrobras 4D data sets acquired for the deepwater Jubarte PRM pilot. By exploiting primary and high-order sea-surface multiples, the reservoir monitoring illumination has been extended from ~ 10 km^2 with conventional imaging to ~ 100 km^2. For future seabed acquisition, the use of this imaging technique gives more flexibility in the design of the receiver layout, allowing sensors to be placed in particularly quiet parts of the seabed, thereby improving the detectability of weak 4D signals without compromising the target illumination. TLE

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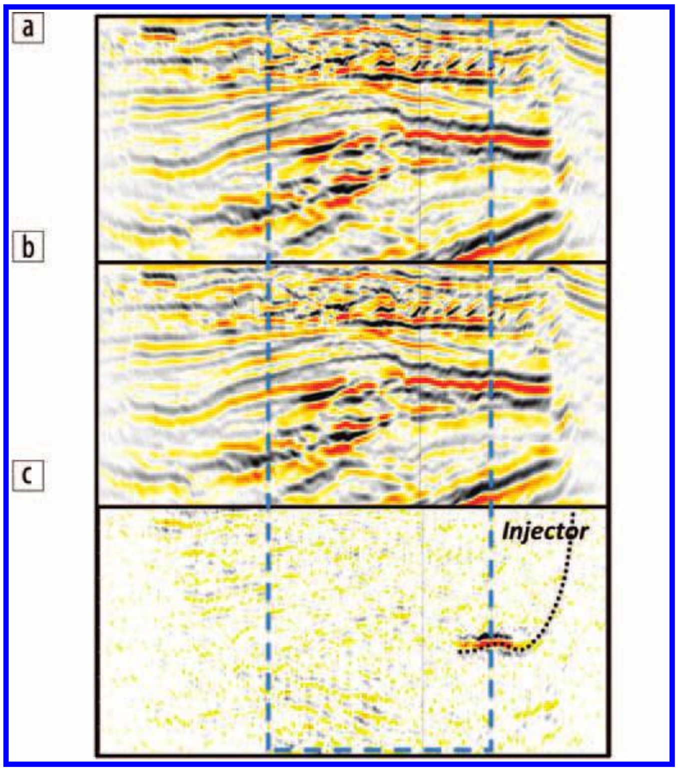

Figure 6. (a) Baseline image using all multiples. (b) Monitor image using all multiples. (c) 4D difference with the injector-well trajectory overlaid. Dashed vertical lines represent the limits of the conventional image obtained by imaging the upgoing wavefield using only primary reflections.

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